Pedestrian and Cyclist Forward Collision Warning System Effectiveness Estimation based on Simulation of Kinematic Reconstructions

François Char

UNIVERSITE D'AIX-MARSEILLE
ED 463- Sciences du Mouvement Humain
Université Gustave Eiffel, LMA
Toyota Motor Europe

Thèse présentée pour obtenir le grade universitaire de docteur

Discipline : Sciences du Mouvement Humain

François CHAR

Estimation des bénéfices apportés en sécurité routière par des avertisseurs de collision frontale pour des piétons et des cyclistes et sensibilité de ces systèmes

Pedestrian and Cyclist Forward Collision Warning System Effectiveness Estimation based on Simulation of Kinematic Reconstructions

Soutenue le 18/12/2020 devant le jury :

Pierre-Jean ARNOUX	Examinator	Université Gustave Eiffel/TS2/LBA
Sabine COMPIGNE	Examinator	Toyota Motor Europe
Nils LUBBE	Reviewer	Chalmers University of Technology (Suède)
Dominique GRUYER	Reviewer	Université Gustave Eiffel/COSYS/PICS-L
Thierry SERRE	Supervisor	Université Gustave Eiffel/TS2/LMA

Numéro national de thèse/suffixe local :

Abstract in French

En 2016, le nombre de morts sur la route atteignait les 1,35 millions dans le monde selon l'Organisation Mondiale de la Santé. 26% de ces morts étaient des piétons et des cyclistes. De nos jours, de plus en plus de véhicules sont équipés de systèmes de d'urgence automatique (appelés FCW - avertisseur de collision frontale) qui peuvent détecter les piétons et les cyclistes et prévenir les conducteurs d'une situation dangereuse. Ces systèmes peuvent aussi participer à l'évitement de collision soit en assistant le conducteur durant le freinage ou en activant un freinage d'urgence automatique (AEB). Cette thèse se concentre sur l'évaluation d'un AEB et d'un FCW piéton et cycliste et a trois objectifs.

Dans un premier temps, plus de 3700 reconstructions d'accidents (2200 cas cyclistes et 1500 cas piétons) ont été analysées provenant de deux bases de données, l'une française et l'autre allemande. Des configurations d'accidents ont été extraites et les cas d'accidents ont été classés en différents scénarios. Un logiciel permettant d'effectuer des simulations a été implémenté de manière à pouvoir rejouer la cinématique des accidents tout en intégrant un AEB avec des caractéristiques adaptables. Cela a permis l'identification des caractéristiques optimums d'un AEB piéton et cycliste en termes de détection d'usager vulnérable de la route mais également du temps de déclenchement d'un FCW et la durée des freinages d'urgences.

Dans un second temps, en se basant sur une expérimentation sur simulateur de conduite, les réactions de conducteurs vis-à-vis du signal d'un FCW ont été analysées dans différentes configurations d'accidents : cas piéton/cycliste, avec ou sans FCW ou encore avec différents timing de déclenchement du FCW. Deux cents participants ont pris part à cette étude sur simulateur. Les résultats expérimentaux extraits concernent l'analyse du regard, la réponse du conducteur au signal du FCW, le temps de réaction pour déclencher un freinage ou encore le comportement en fonction de l'environnement de conduite.

Le troisième objectif concerne l'évaluation des bénéfices du FCW. A partir des résultats de l'étude sur simulateur et des reconstructions cinématiques des cas d'accidents, l'estimation des effets du FCW a été réalisée en termes d'accidents évités ou atténués.

Enfin, des perspectives à ce travail sont proposées.

Abstract

In 2016, road fatalities reached 1.35 million in the world according to the World Health Organization. 26% of these fatalities were pedestrians and cyclists. Nowadays, more and more cars are equipped with an emergency system (called FCW – Forward Collision Warning) that can detect pedestrians and cyclists in order to warn drivers of a hazardous situation. These systems can also help in collision avoidance either by assisting driver during braking or by activating an Automatic Emergency Braking (AEB). This thesis is focused on Pedestrian and Cyclist AEB and FCW assessment and has three main objectives.

First, an analysis on more than 3700 accident case reconstructions (2200 cyclist cases and 1500 pedestrian cases) from two databases, one French and one German has been performed. Accident configurations have been extracted and classified into different scenarios. A simulation software has been implemented in order to replay the accident kinematics with the integration of an AEB by varying their system characteristics. This allows the identification of optimum characteristics for a pedestrian AEB and cyclist AEB in terms of road user detection. It also allows identifying FCW trigger time and the duration of an emergency braking.

Secondly, based on an experimental campaign using a driving simulator, the driver's reactions to a FCW signal have been analyzed on different accident configurations: pedestrian/cyclist cases, with/without FCW and with different FCW triggers. Two hundred volunteers participated in this experiment. The results concern the gaze analysis, the driver's response to the FCW signal, the time reaction to trigger a braking and the different behavior depending on the driving configurations.

The third objective concerns the benefits assessment of a FCW. Based on the results of the driving simulator experiment and the kinematic reconstructions of the accidents, benefits of a FCW are estimated in terms of potential avoided or mitigated accidents.

Finally, some perspectives of this work are proposed.

Keywords: Forward Collision Warning, Automatic Emergency Braking, Pedestrian, Cyclist, Accident reconstruction, Driving simulator

Acknowledgement

I would like to thank everyone who contributed and helped me during this work:

Toyota for funding this research, and all Toyota team members encountered in Belgium and in Japan for their expertise.

Nils Lubbe and Dominique Gruyer for agreeing to be reviewer of this work.

Pierre Jean Arnoux for agreeing to be the president of the jury.

Thierry Serre, my supervisor at Université Gustave Eiffel-LMA for giving me this opportunity, for his expertise, his patience and always being available for my 1 hour little question.

Sabine Compigne, Technical Manager at Toyota Motor Europe for her expertise, her help in the paper writings and her patience.

Pablo Puente Guillen, former researcher at Toyota Motor Europe for his expertise in human factors,

Stéphane and Isabelle Aillerie, Technician and Researcher at Université Gustave Eiffel for their work and assistance during the driving simulator campaign.

Adrien and Bastien Canu, Aurélie Banet, Céline Parraud, Joël Magnin, members of the EDA investigation team of Université Gustave Eiffel -LMA for sharing their knowledge in in-depth crash investigation.

Thierry Brenac and Jean-Yves Fournier, Researcher and Engineer at Université Gustave Eiffel -LMA for their expertise in statistics.

Christophe Perrin, Nicolas Clabaux, Researcher at Université Gustave Eiffel -LMA for sharing their expertise.

Christine Panadour, Anne-Laure Paglia for their help in all administrative tasks.

Romane Cornen for surviving in the same office I was.

Jordan Lecoeuvre for his contribution to this work during his internship.

All the colleagues of Université Gustave Eiffel -LMA and people met during this work for their support.

Family and friends for their invaluable support on this adventure.

Contents

Abstract in French 3
Abstract 4
Acknowledgement 5
Contents 7
Figures 10
Table 16
Preface 19
1. Introduction 20
1.1 Pedestrian and Cyclist accidentology 20
1.1.1 General context 20
1.1.2 Accident scenarios 20
1.1.3 Risk factors 23
1.2 Pedestrian and Cyclist safety 26
1.2.1 General concepts 26
1.2.2 Passive safety 27
1.2.3 Active safety 28
1.3 AEB and FCW system 29
1.3.1 Functioning 29
1.3.2 Driver's reaction 31
1.3.3 Benefits of AEB and FCW 32
1.3.4 Assessment protocols 34
1.4 Research questions 35
1.4.1 Aim and objectives 35
1.4.2 Thesis outline 37
2. Accident analysis and challenges for AEB 39
2.1 Database description 39
2.1.1 In-depth accident investigations 39
2.1.2 Université Gustave Eiffel/LMA EDA 40
2.1.3 GIDAS-PCM 40
2.1.4 Data sample 41
2.1.5 Accident kinematic reconstruction 41
2.2 Tools development 42
2.3 Analyzed parameters 44
2.3.1 Accident scenario 45
2.3.2 AEB characteristics 50

2.3.3 Visibility 51
2.4 Analysis / Challenges / Issues 53
2.4.1 VRU relative position to the car, driver brake activation, vehicle approach speed and accident clustering 53
2.4.2 Field Of View (FOV) 71
2.4.3 Range 80
2.4.4 LTTB and t_{LTTB} 86
2.4.5 Visibility duration before the t_{LTTB} (tvisible-t_{LTTB}) 98
2.5. Conclusion 105
3. Drivers' response to a FCW 108
3.1 Objectives of the driving simulator campaign 108
3.2 Driving simulator 111
3.2.1 General description 111
3.2.3 Video recording 113
3.2.4 Additional elements 114
3.3 Scenario description 116
3.3.1 Which scenario to reproduce and how? 116
3.3.2 Familiarization scenario 119
3.3.3 Pedestrian Longitudinal (P-L) 120
3.3.4 Cyclist Longitudinal (C-L) 121
3.3.5 Turning Left and Pedestrian Left (TL-PL) 123
3.3.6 Turning Left and Pedestrian Right (TL-PR) 124
3.3.7 Turning Right and Pedestrian Right (TR-PR) 124
3.3.8 Turning Left and Cyclist Right (TL-CR) 125
3.4 Secondary tasks 126
3.4.1 Secondary visual-cognitive task 127
3.4.2 Audio-cognitive task 128
3.5 FCW signal 130
3.6 Data collection 131
3.6.1 Driving simulator file 131
3.6.2 Driving simulator video files 133
3.6.3 Facelab eye tracker result files 133
3.6.4 Audio record 135
3.6.5 Questionnaires and interviews 135
3.7 Experimental management 136
3.7.1 Ethical approval 136
3.7.2 Protocol 136
3.7.3 Participant sample and data matrix 137
3.8 Results 139
3.8.1 Pedestrian Longitudinal (P-L) 139

3.8.2 Cyclist Longitudinal (C-L) 143
3.8.3 Turning Left Pedestrian Left (TL-PL) 147
3.8.4 Turning Left Pedestrian Right (TL-PR) 149
3.8.5 Turning Right Pedestrian Right (TR-PR) 151
3.8.6 Turning Left Cyclist Right (TL-CR) 153
3.8.7 Participants' feedback on FCW 154
3.8.8 Main experiment conclusion 156
3.9 Additional experiment 158
3.9.1 New experimental protocol 158
3.9.2 Results 160
3.9.3 Feedbacks on FCW 166
3.9.4 Additional experiment conclusion 167
3.10 Global conclusion 168
4. Benefits evaluation for FCW 172
4.1 Methodology 172
4.1.1 Accident simulation method integrating FCW effects 172
4.1.2 Parametric analysis 176
4.1.3 Factor influences on avoidance rates 178
4.2 Accident simulations 178
4.2.1 Pedestrian accident cases 179
4.2.2 Cyclist accident cases 191
4.2.3 Comparison between Pedestrian and Cyclist cases 202
4.3 Conclusion 204
5. Global conclusion and perspectives 209
5.1 Synthesis and limitations 209
5.2 Perspectives 211
Bibliography 214
Appendix 225
A. Driving simulator preliminary test 226
B. Main experiment questionnaire 259
C. Ethical approval 263
D. Driving simulator main experiment results 275
E. Parametric simulation table per scenario 290

Figures

Figure 1: Fatalities curves evolution for pedestrians and cyclists in Europe. (European Commission 2019b) 20
Figure 2: Main accident scenarios identified by Op den Camp et al. (2016) **Error! Bookmark not defined.**
Figure 3: Pedestrian risk of death in function of the impact speed in the United States (Tefft et al. 2013) 24
Figure 4: Fatalities risk for pedestrians and cyclist in China (Nie et al. 2015) 25
Figure 5: Fatality risk as a function of impact speed in Germany (Rosén and Sander 2009) 25
Figure 6: Pedestrian fatality risk by impact speed (Hussain et al. 2019) 26
Figure 7: Sequences prior the impact with possible action during the different sequences 27
Figure 8: Pedestrian protection test methods proposed by EEVC WG10 (European Enhanced Vehicle-Safety Committee 1998) 28
Figure 9: Example of pedestrian crash on a vehicle from Masson et al. (2007) 28
Figure 10: Illustration of the FOV and range (Meinecke et al. 2005) 30
Figure 11: Accident kinematic reconstruction method 42
Figure 12: Global software development 43
Figure 13: Inputs and outputs of the different software modules 44
Figure 14 : Illustration of UTYP coding for two different cases 46
Figure 15: Chosen scenarios for accident classification, from left to right: turning left; turning right; crossing nearside; crossing farside and longitudinal 47
Figure 16: Decision tree used to classify accident into one of the five accident scenarios or in the "Others" group 48
Figure 17: Illustration of accident cases that are difficult to classify. The accident classification results for those three cases are (from left to right): crossing nearside; longitudinal; turning right) 50
Figure 18: FOV and range sensors modeling 51
Figure 19: Calculus method of the duration tvisible-t_{LTTB} in two configurations: without occlusion on the left (Figure 19a) and with on the right (Figure 19b) 52
Figure 20: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all accidents of our sample (N = 1509) 53
Figure 21: (Left) Cumulative frequency of brake activation timing (51% of all cases) and vehicle approach speed (Right), N = 1509 54
Figure 22: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-CN accidents (N = 788) 55

Figure 23: Drivers' braking timing for the P-CN scenario, 50% braking activation among 788 P-CN accident cases 55
Figure 24: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-CF accidents (N = 461) 56
Figure 25: Drivers' braking timing for the P-CF scenario, 61% braking activation among 461 P-CF accident cases 57
Figure 26: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-L accidents (N = 20) 58
Figure 27: Drivers' braking timing for the P-L scenario, 20% braking activation among 20 P-CF accident cases 58
Figure 28: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-TL accidents (N = 124) 59
Figure 29: Drivers' braking timing for the P-TL scenario, 39% braking activation among 124 P-TL accident cases 59
Figure 30: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-TR accidents (N = 55) 60
Figure 31: Drivers' braking timing for the P-TR scenario, 24% braking activation among 55 P-TR accident cases 61
Figure 32: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all accident of our sample (N = 2261) 62
Figure 33: (Left) Cumulative frequency of brake activation timing (33% of all cases) and vehicle approach speed (Right), N = 2261 62
Figure 34: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-CN accidents (N = 744) 64
Figure 35: Drivers' braking timing for the C-CN scenario, 29% braking activation among 744 C-CN accident cases 64
Figure 36: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-CF accidents (N = 504) 65
Figure 37: Drivers' braking timing for the C-CF scenario, 38% braking activation among 504 C-CF accident cases 65
Figure 38: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-L accidents (N = 120) 66
Figure 39: Drivers' braking timing for the C-L scenario, 33% braking activation among 120 C-L accident cases 66
Figure 40: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-TL accidents (N = 280) 67
Figure 41: Drivers' braking timing for the C-TL scenario, 35% braking activation among 280 C-TL accident cases 68
Figure 42: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-TR accidents (N = 492) 69
Figure 43: Drivers' braking timing for the C-TR scenario, 32% braking activation among 492 C-TR accident cases 69

Figure 44: Rates of visible pedestrian for different FOV for all pedestrian accident cases, N = 1509 ... 71
Figure 45: Rates of visible pedestrian for different FOV for P-CN accident cases, N = 788 ... 72
Figure 46: Rates of visible pedestrian for different FOV for P-CF accident cases, N = 461 ... 73
Figure 47: Rates of visible pedestrian for different FOV for P-L accident cases, N = 20 ... 73
Figure 48: Rates of visible pedestrian for different FOV for P-TL accident cases, N = 124 ... 74
Figure 49: Rates of visible pedestrian for different FOV for P-TR accident cases, N = 55 ... 75
Figure 50: Rates of visible cyclists for different FOV for all Cyclist accident cases, N = 2261 ... 76
Figure 51: Rates of visible cyclists for different FOV for C-CN accident cases, N = 744 ... 76
Figure 52: Rates of visible cyclists for different FOV for C-CF accident cases, N = 504 ... 77
Figure 53: Rates of visible cyclists for different FOV for C-L accident cases, N = 120 . 77
Figure 54: Rates of visible cyclists for different FOV for C-TL accident cases, N = 279 ... 78
Figure 55: Rates of visible cyclists for different FOV for T-CR accident cases, N = 492 ... 78
Figure 56: Range detection rates for all pedestrian cases, N = 1509 ... 81
Figure 57: Range detection rates for pedestrian crossing nearside scenario, N = 78881
Figure 58: Range detection rates for pedestrian crossing farside scenario, N = 461 ... 82
Figure 59: Range detection rates for pedestrian longitudinal scenario, N = 20 ... 82
Figure 60: Range detection rates for pedestrian turning left scenario, N = 124 ... 82
Figure 61: Range detection rates for pedestrian turning right scenario, N = 55 ... 83
Figure 62: Range detection rates for all cyclist cases, N = 2261 ... 83
Figure 63: Range detection rates for cyclist crossing nearside scenario, N = 744 ... 84
Figure 64: Range detection rates for cyclist crossing farside scenario, N = 504 ... 84
Figure 65: Range detection rates for cyclist longitudinal scenario, N = 120 ... 84
Figure 66: Range detection rates for cyclist turning left scenario, N = 280 ... 85
Figure 67: Range detection rates for cyclist turning right scenario, N = 492 ... 85
Figure 68: Pedestrian cumulative detection rates in function of t_{LTTB} for different FOV with a transient state 0.3s (a), a transient state 0.15s (b) or with ideal braking model (c) ... 88
Figure 69: Detection rates at t_{LTTB} for different FOV for the pedestrian crossing nearside scenario, N = 788 ... 89
Figure 70: Detection rates at t_{LTTB} for different FOV for the pedestrian crossing farside scenario, N = 461 ... 89

Figure 71: Detection rates at t_{LTTB} for different FOV for the pedestrian longitudinal scenario, N = 20 90
Figure 72: Detection rates at t_{LTTB} for different FOV for the pedestrian turning left scenario, N = 124 91
Figure 73: Detection rates at t_{LTTB} for different FOV for the pedestrian turning right scenario, N = 55 91
Figure 74: Cyclist cumulative detection rates in function of t_{LTTB} for different FOV with a transient state 0.3s (a), a transient state 0.15s (b) or with ideal braking model (c) 93
Figure 75: Detection rates at t_{LTTB} for different FOV for the cyclist crossing nearside scenario, N = 744 94
Figure 76: Detection rates at t_{LTTB} for different FOV for the cyclist crossing farside scenario, N = 504 95
Figure 77: Detection rates at t_{LTTB} for different FOV for the cyclist longitudinal scenario, N = 120 95
Figure 78: Detection rates at t_{LTTB} for different FOV for the cyclist turning left scenario, N = 280 96
Figure 79: Detection rates at t_{LTTB} for different FOV for the cyclist turning right scenario, N = 492 96
Figure 80: Detection rates at tvisible-t_{LTTB} for all pedestrian cases, N = 1509 98
Figure 81: Detection rates at tvisible-t_{LTTB} for pedestrian crossing nearside cases, N = 788 99
Figure 82: Detection rates at tvisible-t_{LTTB} for pedestrian crossing farside cases, N = 461 99
Figure 83: Detection rates at tvisible-t_{LTTB} for pedestrian longitudinal cases, N = 20 100
Figure 84: Detection rates at tvisible-t_{LTTB} for pedestrian turning left cases, N = 124 100
Figure 85: Detection rates at tvisible-t_{LTTB} for pedestrian turning right cases, N = 55 101
Figure 86: Detection rates at tvisible-t_{LTTB} for all cyclist cases, N = 2261 101
Figure 87: Detection rates at tvisible-t_{LTTB} for cyclist crossing nearside cases, N = 744 102
Figure 88: Detection rates at tvisible-t_{LTTB} for cyclist crossing farside cases, N = 504 102
Figure 89: Detection rates at tvisible-t_{LTTB} for cyclist longitudinal cases, N = 120 103
Figure 90: Detection rates at tvisible-t_{LTTB} for cyclist turning left cases, N = 280 103
Figure 91: Detection rates at tvisible-t_{LTTB} for cyclist turning right cases, N = 492 104
Figure 92: Purpose of the driving simulator campaign 109
Figure 93: Results from the driving simulator experiment 109
Figure 94: General organization of LMA current simulator 112
Figure 95: Driving simulator 113
Figure 96: Example of video recordings 113

Figure 97: Screen for visual-cognitive task....114
Figure 98: Facelab eye tracking device....115
Figure 99: Clock display during video recording....115
Figure 100: Brake deceleration profile of the driving simulator....116
Figure 101: Pedestrian Longitudinal configuration....120
Figure 102: View of the pedestrian set-up (beginning and end) for the P-L scenario....121
Figure 103: Cyclist Longitudinal configuration....122
Figure 104: View of the cyclist set-up (beginning and end) for the C-L scenario....122
Figure 105: Turning Left and Pedestrian Left configuration....123
Figure 106: View of the TL-PL scenario....123
Figure 107: Turning Left Pedestrian Right configuration....124
Figure 108: View of the TL-PR scenario....124
Figure 109: Turning Right and Pedestrian Right configuration....125
Figure 110: View of the TR-PR scenario....125
Figure 111: Turning Left Cyclist Right configuration....126
Figure 112: View of the TL-CR scenario....126
Figure 113: Forkenbrock et al. (2011) distraction task sequence....127
Figure 114: Example of visual task for Cyclist Longitudinal scenario. The progress is the same for Pedestrian Longitudinal....128
Figure 115: Audio-cognitive task and participant's answer progress....129
Figure 116: Audio FCW specification....130
Figure 117: Visual display of FCW signal on the simulator screen and from passenger seat point of view....130
Figure 118: Gas and brake pedal time extraction....132
Figure 119: Algorithm for creating videos with gaze location....135
Figure 120: Gas pedal release boxplot for P-L scenario....141
Figure 121: Brake pedal trigger boxplot for P-L scenario....141
Figure 122: Gas pedal release boxplot for C-L scenario....145
Figure 123: Brake trigger time boxplot for C-L scenario....146
Figure 124: Gas pedal release time for TL-PL scenario....148
Figure 125: Boxplot of the brake trigger time for TL-PL scenario....148
Figure 126: Gas release time boxplot for TL-PR scenario....150
Figure 127: Brake trigger time boxplot for TL-PR scenario....150
Figure 128: Gas pedal release boxplot for TR-PR scenario....152
Figure 129: Brake trigger boxplot for TR-PR scenario....153
Figure 130: Images of the TL-CR scenario before and after the cyclist appearance....159
Figure 131: Gas release time for new TL-PL scenario....162
Figure 132: Brake trigger time for new TL-PL scenario....162
Figure 133: Gas release trigger boxplot for the new TL-CR scenario....165
Figure 134: Brake trigger time for new scenario TL-CR scenario....165
Figure 135: FCW trigger model in the simulation....173

Figure 136: Accident simulation algorithm integrating FCW effect 175
Figure 137: Reconstruction simulation example integrating the effect of FCW for two FCW parameter settings 176
Figure 138: Results of the parametric analysis for all pedestrian accidents (N = 1509) 179
Figure 139: Results of the parametric analysis for the P-CN scenario (N = 788) 181
Figure 140: Results of the parametric analysis for the P-CF scenario (N = 461).........181
Figure 141: Results of the parametric analysis for the P-L scenario (N = 20) 182
Figure 142: Results of the parametric analysis for the P-TL scenario (N = 124).........183
Figure 143: Results of the parametric analysis for P-TR scenario (N = 55) 184
Figure 144: Results of the 3 factor ANOVA test for all pedestrian cases (N = 1509) .186
Figure 145: Results of the 3 factor ANOVA test for P-CN cases (N = 788)......................187
Figure 146: Results of the 3 factor ANOVA test for P-CF cases (N = 461) 188
Figure 147: Results of the 3 factor ANOVA test for P-L cases (N = 20)...........................189
Figure 148: Three factor ANOVA complement without the non-significant factors ..189
Figure 149: Results of the 3 factor ANOVA for P-TL cases (N = 124)..............................190
Figure 150: Results of the 3 actor ANOVA for P-TR case (N = 55) 190
Figure 151: Results of the parametric analysis for all cyclist accidents (N = 2261)...192
Figure 152: Results of the parametric analysis for C-CN scenario (N = 744)................193
Figure 153: Results of the parametric analysis for C-CF scenario (N = 504) 194
Figure 154: Results of the parametric analysis for C-L scenario (N = 120) 195
Figure 155: Results of the parametric analysis for C-TL scenario (N = 280) 195
Figure 156: Results of the parametric analysis for C-TR scenario (N = 492)................196
Figure 157: Results of the 3 factor ANOVA test for all cyclist cases (N = 2261) 197
Figure 158: Results of the 3 factor ANOVA test for C-CN (N = 744) 198
Figure 159: Results of the 3 factor ANOVA test for C-CF cases (N = 504) 199
Figure 160: Results of the 3 factors ANOVA for C-L cases (N = 120)...............................199
Figure 161: Results of the 3 factor ANOVA test for C-TL cases (N = 280) 200
Figure 162: Results of the 3 factors test for the C-TR cases (N = 492) 201

Table

Table 1: Main identified scenario proportion from literature review for pedestrian accidents .... **Error! Bookmark not defined.**
Table 2: Main identified scenario proportion from literature review for cyclist accidents .... **Error! Bookmark not defined.**
Table 3: A priori estimation of FCW effects 34
Table 4: A posteriori estimation of FCW effects 34
Table 4: Accident case numbers extracted from the databases 41
Table 5: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.15s) 88
Table 6: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.3s) 88
Table 7: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.15s) 93
Table 8: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.3s) 94
Table 9: Proportion of accident cases classified into the different identified scenarios 105
Table 10: Main results on accident kinematic reconstruction analysis 106
Table 11: General characteristics extracted from accident visual analysis 117
Table 12: Additional characteristics extracted for Longitudinal and Turning scenarios 117
Table 13: Results of the characteristic extraction for each cyclist scenario 118
Table 14: Results of the characteristic extraction for each pedestrian scenario 119
Table 15: Experimental session for each participant 137
Table 16: Planned data matrix 137
Table 17: Actual data distribution for each scenario and each condition 139
Table 18: Results data for P-L scenario 139
Table 19: Driver reaction times for P-L scenario with a FCW 2s 140
Table 20: Mean reaction values for different distraction level for the P-L scenario 142
Table 21: Results data for C-L scenario 144
Table 22: Driver reaction times for C-L with a FCW 2s and FCW 1.7s 144
Table 23: Mean reaction time for different distraction level 146
Table 24: Results data for the TL-PL scenario 148
Table 25: Results data for TL-PR scenario 149
Table 26: Driver reaction times for TL-PR with a FCW 2s 149
Table 27: Results data for the TR-PR scenario 151
Table 28: Driver reaction times for TR-PR with a FCW 2s and FCW 1.7s 152

Table 29: Results data for the TL-CR scenario 154
Table 30: Potential driver reactions time to a FCW split according to FCW trigger times 157
Table 31: Results data for the new TL-PL scenario 160
Table 32: Driver reaction times for new TL-PL with a FCW 2s 161
Table 33: Results data for the new TL-CR scenario 164
Table 34: Driver reaction times for new TL-CR with a FCW 2s 164
Table 35: Potential driver reaction times to a FCW split according to FCW trigger times for the new scenarios 168
Table 36: Parameter combinations that allow reaching a maximum avoidance and mitigation rate and at least 50% avoidance in most scenarios 184
Table 37: Correspondence between factors 185
Table 38: Factor order of importance for P-All cases (N = 1509) 186
Table 39: Factor order of importance for P-CN cases (N = 788) 187
Table 40: Factor order of importance for P-CF cases (N = 461) 188
Table 41: Factor order of importance for P-L cases (N = 20) 189
Table 42: Factor order of importance for P-TL cases (N = 124) 190
Table 43: Factor order of importance for P-TR case (N = 55) 191
Table 44: Global view of the factor influence order on the different pedestrian scenarios 191
Table 45: Parameter combinations that allow reaching a maximum avoidance and mitigation rate and at least 50% avoidance in most scenarios 197
Table 46: Factor order of importance for C-All cases (N = 2261) 197
Table 47: Factor order of importance for the C-CN (N = 744) 198
Table 48: Factor order of importance for C-CF cases (N = 504) 199
Table 49: Factor order of importance for C-L cases (N = 120) 200
Table 50: Factor order of importance for C-TL cases (N = 280) 200
Table 51: Factor order of importance for C-TR cases (N = 492) 201
Table 52: Global view of the factor influence order on the different cyclist scenarios 201

Preface

Since 2008, Toyota Motor Europe NV/SA and IFSTTAR (the French institute of science and technology for transport, development and networks) are collaborating on different research projects. Among them, the VRU-SIM project which started in 2016 and aimed at estimating the safety benefits of pedestrian and cyclist Forward Collision Warning system and the sensibility to system parameters.

This project was under the supervision of IFSTTAR and Toyota researchers. It was funded by Toyota and followed the work of Hédi Hamdane on the improvement of pedestrian safety that ended in 2016. Two interns also contributed to this project, Guillaume Lechevallier for two months and Jordan Lecoeuvre for six months. The project ended in 2019 with the delivery of deliverables and with a presentation in Japan.

During the course of the project, IFSTTAR merged in 2020 with other entities and became the first French national university, Université Gustave Eiffel.

1. Introduction

1.1 Pedestrian and Cyclist accidentology

1.1.1 General context

In 2016, 1.35 million road deaths can be counted making it the eighth leading death cause worldwide according to the World Health organization (WHO 2018). Still a high proportion of those deaths concern pedestrians or cyclists which worldwide globally represent respectively 23% and 3% with disparities.

Approaching to the end of the Decade of Action for Road Safety, the objective for road safety was to halve the number of road deaths by 2020. In Europe, even if road fatalities were reduced by 21% in 2018 compared to 2010, the objective may not be reached. Pedestrians' fatalities decreased by 15% from 2010 to 2017 and reached 21% whereas for cyclists, the decrease was only of 2% for the same period reaching 8% (European Commission 2019a). So it appears important to develop the pedestrian and cyclist road safety according to the issue that it represents. Figure 1 illustrates fatalities evolution curves for pedestrians and cyclists in Europe during the last years.

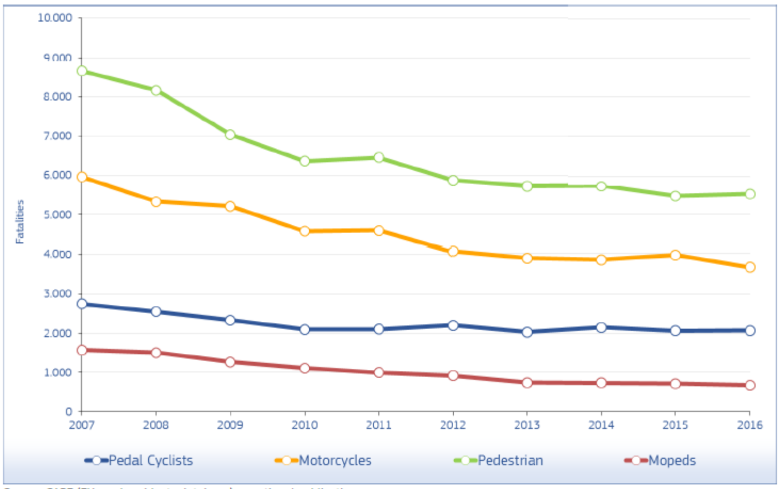


Figure 1: Fatalities curves evolution for pedestrians and cyclists in Europe. (European Commission 2019b)

1.1.2 Accident scenarios

The identification of the most frequent accident scenarios is the first step in order to determine the challenges and issues for pedestrian and cyclist safety. Through it, the best or at least the most appropriate measures can then be taken. To that end, many researches have been performed in that way since the 1990s with the identification of cyclist and pedestrian accident scenarios in the United States (Hunter et al. 1997a; Hunter et al. 1997b). Brenac et al. (2003) identified accident scenarios and their proportion in France where a pedestrian was involved. Based on the analysis of vFFS Group on the GIDAS database, their identification of pedestrian scenarios had been reused in the European project AsPeCSS (Schaller et al. 2012). Blower (2014) identified key pedestrian collision scenarios for avoidance technologies in the United States. In 2015, French accident scenarios were extracted through the reconstructions of a sample of 100 accidents where a pedestrian was injured (Guillaume et al. 2015). The same year, by combining different databases, Martin and Wu (2015) extracted French pedestrian accident scenarios and also proposed a weighting method to be representative of France accidentology for their scenarios. The scenario identification work can also be found for cyclist as it can be seen in different researches. MacAlister and Zuby (2015) extracted cyclist accident scenarios in United States for the design of cyclist detection system. In Germany, Kuehn et al. (2015) performed a similar work using a database from German Insurers. In France, Clabaux and Brenac (2010) identified urban accidents involving cyclists. Scenario identification can also be found in different projects. In AsPeCSS project (The Assessment Methodologies for Forward Looking Integrated Pedestrian and Further Extension to Cyclists Safety Systems)(Rodarius et al. 2014), cyclist accident scenario identification was performed for the Netherland and for the United Kingdom. They proposed an urban crossing, a turning right and left and an inter-urban longitudinal scenario. In “CATS: Cyclist-AEB-Testing System” project (Uittenbogaard et al. 2016a; Uittenbogaard et al. 2016b), they proposed test scenarios with consideration of the car and cyclist trajectories and without taking into account the infrastructure. Scenarios found were a cyclist crossing from the left or the right when a car is going straight, the car turning to the left or to the right with cyclist coming from different origin and a car going straight with a cyclist going also straight or coming on the opposite direction. In the “Proactive Safety for Pedestrians and Cyclists” (Prospect project) (Wisch et al. 2016), cyclist scenarios were extracted for different European countries in order to be extended for Europe. They proposed scenarios where a car is going straight with a crossing cyclist, car turning with different cyclist origin and a car is going straight with a cyclist going in the same direction as the car. This literature feeds the Euro NCAP consumer organization who has progressively integrated new scenarios in their test protocols (see section 1.3.4).

Accidents can be also classified into different groups depending on the object of interest. Huang et al. (2006) worked on STRADA, a Swedish database to analyze the requirement for pedestrian detection sensors located in a car. They extracted 2 scenarios: a pedestrian crosses before or after the intersection and a passenger car is going straight forward. Jermakian and Zuby (2011) and Blower (2014) analyzed two American databases to extract their accident scenarios. Jermakian and Zuby (2011) extracted three scenarios with consideration of both car and pedestrian trajectory. They considered a car going straight and a pedestrian crossing, a car going straight and a pedestrian walking straight in-line with traffic and a car turning and a pedestrian crossing. In a similar way, Blower (2014) also identified pedestrian scenarios based on both trajectories in order to identify requirements for collision avoidance technology. With the identification of accident scenarios for pedestrian, assessment programs have started to integrate them progressively in the car rating system since 2014. This way, Euro NCAP (2015) presented an assessment protocol with precise testing configurations. They proposed to evaluate crossing situations with pedestrian coming from the left or right side of the car. They also proposed a scenario with a crossing child instead of an adult coming from the right with visual occlusion. They also added in 2019 new scenarios which concern turning manoeuvers (Euro NCAP 2019b) which were not previously addressed.

As the VRU safety does not only concern pedestrian, it was planned to also focus on cyclist. Many researches analyze cyclist accidents in order to extract accident scenarios. Kuehn et al. (2015) analyzed a database created by the German Insurers Accident Research that contained accident cases where damage costs were higher than 15,000€. They identified three main scenarios, a car traveling straight with a cyclist coming from the right, a car turning to the right with a cyclist coming from the right and a car going straight with a cyclist coming from the left. MacAlister and Zuby (2015) extracted cyclist scenarios from two American databases. They have considered the trajectories of both car and cyclist and found scenarios in which a car is going straight with a cyclist traveling in-line or against the traffic, a car is going straight with a crossing cyclist or a car turning at an intersection with different origin for the cyclist. From these literature review and different projects, assessment protocol proposition appears in 2017 for cyclists (Euro NCAP 2017c). The scenarios in this test protocol were similar than pedestrian ones with one additional configuration, a longitudinal scenario. The longitudinal scenario is a configuration in which a car and a cyclist are going straight forward in the same direction. This is a configuration that can be usually encountered when driving. Thus, it appears natural to also analyze this type of configuration.

As it can be seen, the literature review shows lots of different accident scenarios and some common characteristics that can be found in different researches. Assessment programs have included the most common and frequently encountered scenarios in the evaluation of car safety. However as it can be noticed, some configurations were not addressed yet until recently. As an example the turning configurations have been added only recently as a scenario for pedestrians and is still not included for cyclists (Euro NCAP 2019b).

The following tables give a summary of the main scenarios identified in the major studies. **Error! Reference source not found.** is an illustration example of accident scenarios.

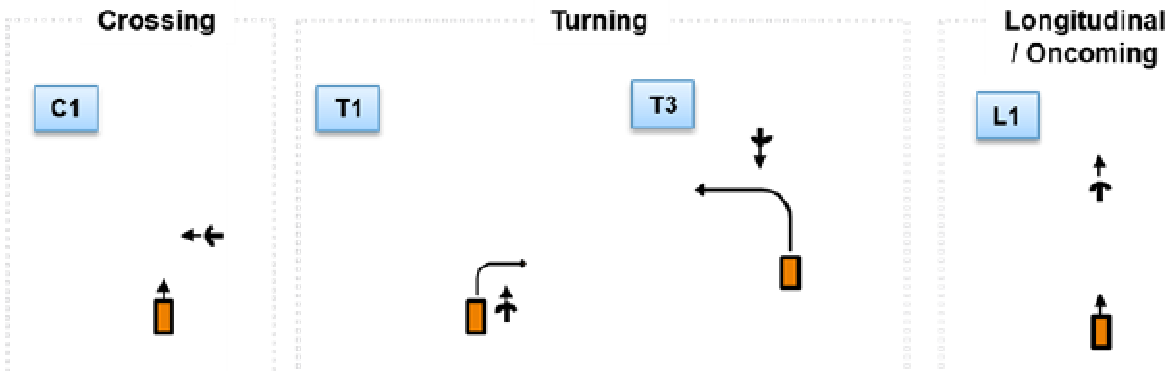


Figure 2: Main accident scenarios identified by Op den Camp et al. (2016)

	Crossing	Turning	Longitudinal	Others	Total	Country	Representative
Schaller (2012)	74.3%	11.2%	3.3%	11.2%	100%	Germany	Not mentioned
Blower (2014)	36.7%	30.1%	4.4%	28.8%	100%	US	Yes
Guillaume (2015)	83%	Include in Others	7%	10%	100%	France	No
Martin (2015)	53.7%	15.4%	3.2	27.7	100%	France	Yes
Brenac (2003)	56%	5.8%	4.3%	33.9%	100%	France	Yes *

* The scenarios are relevant but the proportions might be a little different

Table 1: Main identified scenario proportion from literature review for pedestrian accidents

	Crossing	Turning	Longitudinal	Others	Total	Country	Representative
MacAlister (2015)	Not known	Not known	Not known	Not known	100%	US	Yes
Rodarius (2014)	28.1%	35.2%	10.7%	26%	100%	UK	Yes
	40% or more	20% or more	Not known	Not known	100%	Netherlands	Yes
Uittenbogaard (2016a)	55.5%	9.5%	16.5%	18.5	100%	France Germany Italy Netherlands Sweden UK	No
Kuehn (2015)	~32% or more	~17% or more	Not known	Not known	100%	Germany	No

Table 2: Main identified scenario proportion from literature review for cyclist accidents

1.1.3 Risk factors

Thank to scenario identification and accident analysis, it is also possible to determine and evaluate risk factors for pedestrians and cyclists safety. Impact speed is indeed a risk factor for vulnerable road users (VRU) that can induce severe or fatal injuries. A review of literature was performed by Rosén et al. (2011) for pedestrians about the speed factors. Tefft (2013) analyzed risk factors in function of the speed and also included age criteria.

Fredriksson and Rosén (2012) analyzed the combination of active and passive countermeasures for the head injuries in pedestrian accidents. Similarly, risk factors can also be seen through another point of view as done by Keall et al. (2014). They analyzed the evolution of fatal and severe injuries for pedestrians according to renewal of vehicle fleet in Australia and New Zealand. Wang et al. (2017) analyzed risk encountered for different transport modes: cars, pedestrians or cyclists. As seen for pedestrians, Martinez-Ruiz et al. (2015) analyzed the cyclist risks in Spain according to gender and age parameters. Reynolds et al. (2009), Vandenbulcke et al. (2014) and Robartes and Chen (2017) determined the cycling risk by taking into account factors like infrastructure, environment, and traffic. With the risk information, acting on some of those factors could be an effective way for injury reduction. Indeed, a strong impact could be realized to switch the proportion of fatal to severe injury, and severe to light injury. Thus, through the combination of multiple factors, a more or less important offset effect can be achieved.

The following Figure 3 to Figure 6 show the risk curves for pedestrian and cyclists obtained by different authors and show difference according to the considered countries.

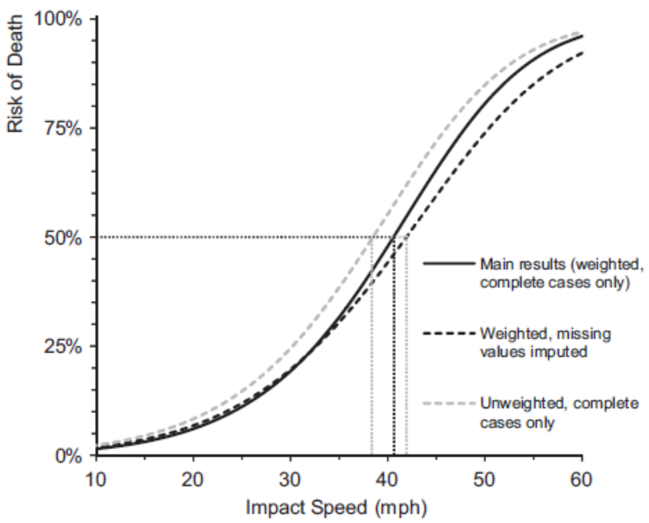


Figure 3: Pedestrian risk of death in function of the impact speed in the United States (Tefft et al. 2013)

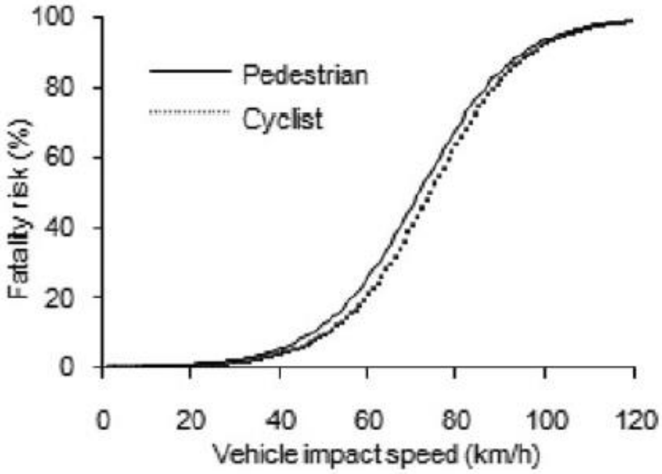


Figure 4: Fatalities risk for pedestrians and cyclist in China (Nie et al. 2015)

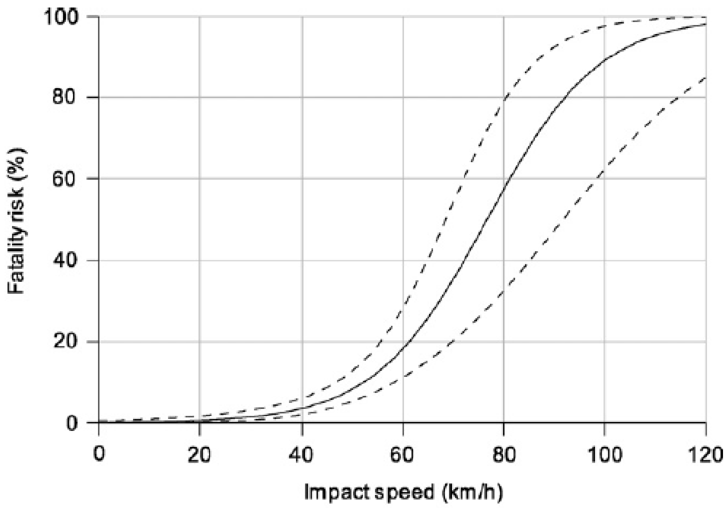


Figure 5: Fatality risk as a function of impact speed in Germany (Rosén and Sander 2009)

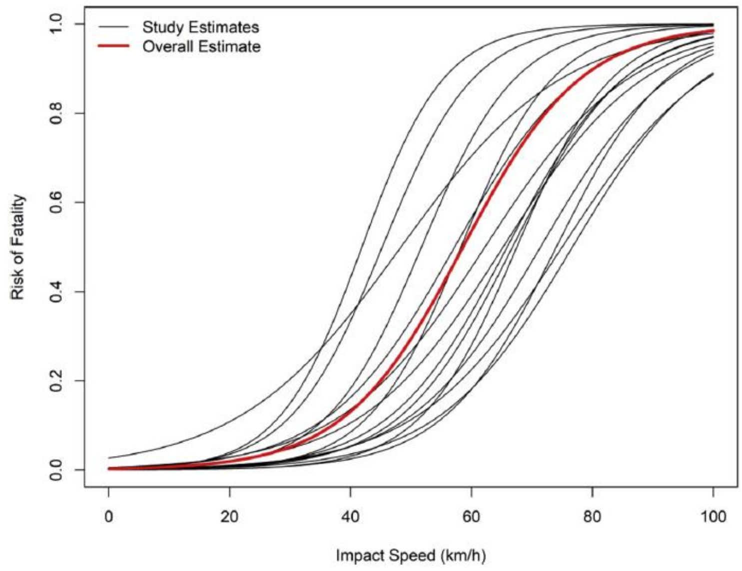


Figure 6: Pedestrian fatality risk by impact speed (Hussain et al. 2019)

The VRU displacement speed can also have an influence. Indeed, the displacement speed combined to other factor like occlusion for example can also then be a factor in car-to-VRU crashes. Pedestrians are usually considered walking at 5km/h (Huang et al. 2008) which is low speed compared to bicycle one. Schleinitz et al. (2017) found on a naturalistic study that cyclist speed reached up to 45 km/h with electric assistance compared to the 25km/h without. As we will see later, this significant difference in displacement speed can greatly affect detection system and thus their effectiveness.

1.2 Pedestrian and Cyclist safety

1.2.1 General concepts

In order to determine how positively VRU safety can be improved, it is necessary to understand and describe what an accident is. Ferrandez et al. (1995) identified and described the four different phases constitutive of an accident. At first, there is a “normal driving situation” in which the driving task is normal and under control by the driver. In accident scenario, the normal driving situation is interrupted by a rupture situation. This rupture which is of a short duration corresponds to an unexpected event that is the transition between the normal driving situation to the emergency situation. During the emergency situation, a time and space limited problem is presented to the driver which has to resolve it. However, the accident still occur whatever the emergency manoeuver engaged by the driver, meaning that the manoeuver has failed. Thus, the emergency situation leads to the fourth and final phase: the crash.

The general objectives to protect the pedestrian and the cyclist during an accident are summarized in the following Figure 7:

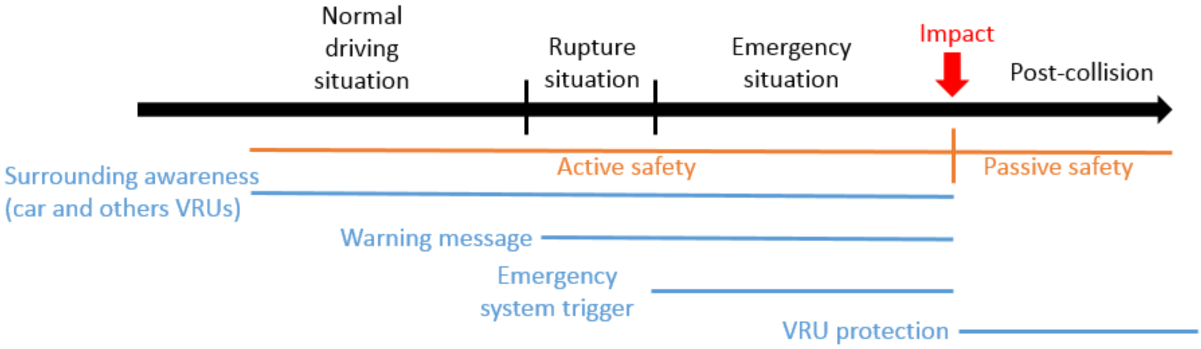


Figure 7: Sequences prior the impact with possible action during the different sequences

Prior a crash, safety systems can be spread into active and passive. Active safety systems regroup all features that can avoid or reduce the severity of a collision contrary to passive safety which objective is only to reduce or decrease the consequence after the collision happens. Among the active safety features, we can find systems that allow the driver to be aware of the surroundings environment and other road users like pedestrians or cyclists or warn the driver of a hazard. It can also signal the driver to act in order to react to an emergency situation. On the opposite side, among passive safety features, seatbelt and airbag can be found for drivers' safety. For VRUs, car flexible structures allow the absorption of a part of the energy during the collision as airbag combined with rising hood to reduce VRU injuries. The combination of both active and safety features are complementary and will be described with more details in next sections.

1.2.2 Passive safety

Concerning the crash phase, passive safety systems have been developed to protect and limit as far as possible the impact against the car. From a global point of view, the main objective of the passive safety is to build car less aggressive for the VRU (Serre 2009). When a vehicle strikes the pedestrian, there are three main body regions injured: the impact of the lower limb on the bumper, the impact of the pelvis on the lower part of the bonnet and the impact of the head of the bonnet or the windscreen as illustrated by the test protocol in Figure 8 and a test example in Figure 9.

New proposals exist to improve road safety for VRU. Among them, we can find a device composed of an airbag and a rising hood. This device is supposed to reduce injuries for a pedestrian being hit by a passenger car. Many evaluations have been proposed and performed. Maki et al. (2003) described such system to analyze pedestrian collision kinematic. Holding et al. (2001) studied a pedestrian airbag to determine pedestrian proximity detection for the triggering of the device and found important injuries reduction with this kind of system. Yang et al. (2015) and Lim et al. (2014) performed evaluation for the airbag and hood system design. The objective of the first was to determine the design parameters of the device using experiments whereas the second aimed at determining head injuries reduction. In a similar way as Lim et al. (2014), Fredriksson and Rosén (2012) evaluated the potential head injuries reduction for hood and airbag device.

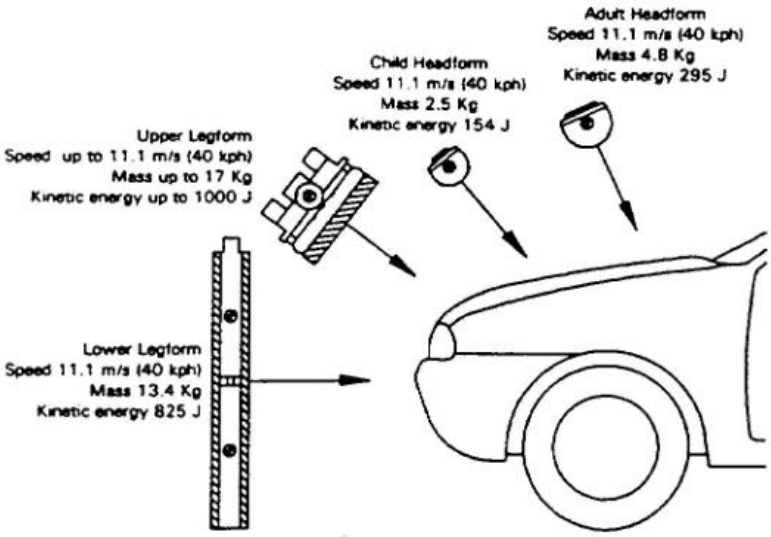


Figure 8: Pedestrian protection test methods proposed by EEVC WG10 (European Enhanced Vehicle-Safety Committee 1998)

Figure 9: Example of pedestrian crash on a vehicle from Masson et al. (2007)

1.2.3 Active safety

Concerning the active safety, it consists to avoid the accidents as far as possible or at least reduce the impact speed. Indeed, after a rupture phase has been identified, the earlier an intervention can be performed during the emergency situation, the better effect can be achieved. So, the objective is first to prevent or alert the driver or/and the VRU about their respective presence and secondly to deploy systems in order to avoid or mitigate the impact. This way, Advanced Driver Assistance System (ADAS) can be of great help.

Technologic proposal concerns communication systems that send a message to vehicle drivers and/or to VRU. Many different communication systems can be found like vehicle-to-everything (V2X), vehicle-to-pedestrian (V2P), vehicle-to-cyclist (V2C) and also vehicle-to-infrastructure (V2I) and vice versa. In this type of system, the main goal is to warn the receiver of a dangerous situation or simply to report to be careful. Rahimian et al. (2018) proposed a mobile device to warn pedestrians of an unsafe crossing with a communication system between vehicle and pedestrian mobile phone. Wu et al. (2014) proposed a warning system that warns users (car and VRU) of a collision. Hussein et al. (2016) went further with a system that communicates in both directions from vehicle to pedestrian and also vice versa. Bagheri et al. (2014) and Anaya et al. (2014) developed mobile application with the objective to warn walking pedestrian.

Other original ideas can be found like a system that warns VRU in the situation of a collision. It is the case of Van Brummelen et al. (2016) who proposed a cyclist low cost device based on laser and ultrasonic sensors to warn cyclist through a haptic signal. Jeon and Rajamani (2018) proposed a similar system which should work for collision with vehicle rear and right-turning vehicle at a traffic intersection.

Assistance technologies can either alert or avoid the accident. Through information gathered by sensors and merged together, vehicles have now the possibility to warn of hazard during the driving so the driver can take appropriate measures. This can be performed by a Forward Collision Warning (FCW). In the case of no reaction from the driver, vehicle system can decide to perform an Automatic Emergency Braking (AEB).

So, between AEB and FCW device, only the final aim is different. An AEB system triggers automatically and does not need a human intervention contrary to a FCW where human is in the center of the loop. These two ADAS are developed in the next section.

1.3 AEB and FCW system

1.3.1 Functioning

In a general way, AEB and FCW system work in a similar way. Those systems observe, identify, track and take appropriate action according to the situation. The observation step consists of monitoring the surroundings with the help of the different sensors mounted on the vehicle. Data gathered will be used in the identification step. Depending on the sensor specificities, different methods will be used to correctly identify what is present in the environment. Then, the identified element like VRUs and other cars can be tracked. The tracking will be used in order to determine potential collision. In that case, a decision algorithm intervenes to determine if an AEB or FCW system triggering is required and when so the driver can act.

The sensors system is similar for both AEB and FCW composed of the combination of multiple different sensors like a camera, radar, LIDAR or infrared radiation (IR). Camera allows identification and tracking of elements in the vehicle surrounding (Fardi and al. 2006a). LIDAR and radar use time-of-flight to create a precise map of the surrounding environment (Fuerstenberg and Willhoeft 2001; Szarvas et al. 2006). Infrared radiation can be used to distinguish difference of temperature between human body and the environment (Fardi et al. 2006b). Each sensor has it strength and weakness and is complementary. For example cameras are strongly affected by lighting conditions contrary to LIDAR and radar (Fritsche et al. 2017). Object recognition is more difficult for LIDAR and radar whereas for camera, this process can be more effective depending on the learning model behind. A review of sensors technologies is made by Gandhi and Trivedi (2007).

Two parameters are in particular important for the sensors in the detection of the VRU: the Field of View (FOV) and the Range (Figure 10). The field of view represents the detection cone angle in front of the sensors and is usually described in degrees. The range corresponds to the detection distance reachable by sensors mentioned in meters.

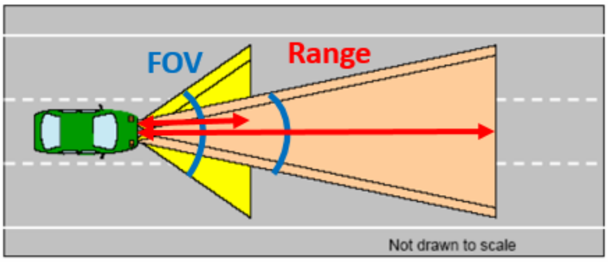


Figure 10: Illustration of the FOV and range (Meinecke et al. 2005)

Thus merging data from these different sources allows detection system to be more robust and accurate even if it remains possible to have only one sensor system. Bertozzi et al. 2006, Meinecke et al. 2005, Scheunert et al. 2004, Szarvas et al. 2006 are examples that illustrates sensor combination for pedestrian detection. Gavrila et al. (2004) and Geronimo et al. (2010) used camera only for pedestrian detection system as did Li et al. (2016) for cyclist detection.

In the case of a FCW, other multiple factors have to be taken into account like the trigger timing of the system according to the drivers' reaction time to the system. Those are the two main visible factors that have to be considered for the evaluation of such device. However, many difficulties can be found in the FCW design. Among them, we can quote the difficulties to correctly recognize VRU, predicting a collision path between the vehicle and a VRU path (Meijer et al. 2017), determining the most appropriate trigger timing to alarm drivers for example. Thus, establishing a correct and exhaustive evaluation for FCW appears to be a complex task that requires multidisciplinary skills.

1.3.2 Driver's reaction

The objective of this research is to determine the benefits a FCW can achieve for pedestrian and cyclist safety. To that end, it is necessary to take into account how drivers will react. However, understanding and modeling drivers' reaction is a difficult task. That is why, the choice of driver reaction model is crucial in order to be able to correctly evaluate FCW effect. A review of drivers' reaction literature is given in order to highlight the difficulty to choose a driver model. In this PhD, a driving simulation will be performed to extract a mean behavior to a FCW in different scenario configurations.

A lot of researches about driver's reaction can be found in the literature. This topic has always been of interest as its understanding can lead to model a driver behavior, models that can be used for system evaluation for example. Van der Hulst et al. (1999) analyzed driver's behavior in a car following task with different deceleration level of a lead vehicle in expected or unexpected situations. In their analysis, they analyzed the two components of driver's reaction: the time from the perception of a signal to the release of the accelerator pedal and the time from the release of the accelerator pedal to the depression of the brake pedal. This way, they were able to compare drivers' reaction for different driving situations. Drivers' reaction literature review can also be found in Young and Stanton (2007) and in Wood and Zhang (2017). The first analyzed drivers' reaction in non-automated vehicle through a driving simulation study whereas the second used naturalistic driving data. Nevertheless, reaction towards a FCW to evaluate headway distance for a car following task can be found in the literature as the one performed by Aksan et al. (2016) for different age groups. Depending of the objective a FCW would reach, the design of such system requires to be carefully considered. Dozza et al. (2017) helped in designing an effective FCW system by highlighting relevant factors. Also, as mentioned by Bärgman et al. (2017) the choice of driver reaction model is of importance.

Different types of signal can be used in order to inform drivers. It can be audio, visual or also haptic signal alone or a multiple combination of them. Campbell et al. (2007) made a review of human factors knowledge that can have an application in the conception of audio, visual or haptic warnings. They also gave guidance and recommendations for FCW design and also for others ADAS as well. Depending on the considered signal, drivers' reaction can be improved. Lylykangas et al. (2016) analyzed drivers' reaction time in emergency scenarios with FCW. They found that tactile and visual-tactile signals help drivers react faster compared to an only visual signal.

Aust et al. (2013) also analyzed a combination of audio and visual signal in order to study FCW effect for repeatedly exposure on emergency braking. They found that the more drivers were exposed to FCW, the faster they can react to the signal. This is also confirmed by Koustanaï et al. (2012) where the FCW was more effective with familiarized drivers compared to unfamiliarized.

Prior evaluating drivers' reaction towards a FCW, it is well known that many factors have to be taken into account. Either the perception reaction time or on the movement time (time to release the gas pedal to the depression of the brake pedal) are affected by age or gender as shown by Warshawsky-Livne and Shinar (2002). The reaction time can also be affected by the expectation of an event (Wood and Zhang 2017). Schweitzer et al. (1995) made a comparison of the total braking time (TBT) reaction based on three awareness levels. They found that the more expected is an event, the faster drivers react to it. Similarly, Abe and Richardson (2006) worked on the effect on trust and driver expectation from FCW system. They showed that faster reactions could be obtained when an earlier alarm is triggered. Thus, it appears obvious that the earlier a warning is given, the best reaction can be achieved. However, Zador et al. (2000) analyzed that effect based on the trigger time. They found that driver's trust and acceptance can be affected if an alarm is given too early. Indeed, it might appear as a false warning. On the other side, a too late alarm may decrease the trust in the system. This highlights once again a crucial parameter which is the warning time of the system. Nevertheless, when the system is completely reliable, hazard detection is faster as shown by Bueno et al. (2012) for motorcycle detection. Thus, avoidance strategies can appear. Wu et al. (2017) analyzed this effect for FCW for rear-end collision and found two different behaviors, braking and steering. However, performance can be affected by distraction.

Disturbing elements can be present in the surrounding environment and need to be measured (Strayer et al. 2013). Still, FCW can have a positive effect. Bueno et al. (2014) found positive effect of FCW in the case of low distracted drivers. However, on highly distracted drivers, FCW effects disappear underlying the necessity of attentional resources to process the warning signal. Harbluk et al. (2007) study reveals that depending on the distraction level, visual behavior and braking performance can be affected. Thus being able to predict drivers' intention might be an interesting lead as it can help either to know if a warning system has to be triggered and also when. Diederichs et al. (2015) made this kind of analysis with the idea to avoid annoyance before initiating an automatic system trigger like an AEB. This idea is more than of interest in the case of a FCW. In order to highlight FCW potential safety, more knowledge about driver model is required in order to correctly evaluate FCW efficiency (Bärgman et al. 2017). Puente Guillen and Gohl (2019) proposed that FCW should be elaborated based on a driver model. However, finding the appropriate model is still a challenge nowadays.

1.3.3 Benefits of AEB and FCW

With the apparition of ADAS, several studies had been performed in order to determine their potential benefits on road safety (Coelingh et al 2010; Jermakian (2011); Zhao et al. 2017). Among the different ADAS that can be found in the market, a focus will be given here on AEB and FCW. Those two safety systems started appearing in the 2000s and were designed to improve road safety.

Thus evaluations of these systems have been conducted to determine their effect on driving. Initial evaluations were performed on rear-end crash between two cars

(Forkenbrock and O'Harra 2009; Forkenbrock et al. 2011). The aims of those studies were to determine an appropriate trigger time for a FCW system and also drivers' reaction to the trigger. Fildes et al. (2015) also made an analysis on rear-end crash reduction for a car-to-car AEB system and found an effect of 38%. In a similar way, Seacrist et al. (2019) evaluated AEB for rear-end crash using simulation on naturalistic rear-end crashes and found that a rate of 80% effectiveness can be reached.

After considering car-to-car rear end crashes, accidents involving different VRU had been also considered. Introduced first for pedestrians, studies can be found evaluating AEB effect for pedestrian accident scenarios like in Rosén et al. (2010) or the combination of FCW and AEB as in Coelingh et al. (2010) or in Lubbe and Kullgren (2015). Hamdane et al. (2015) identified the issues and challenges for a pedestrian AEB for real world accidents. Concerning cyclists, Lenard et al. (2018) made an analysis on cyclist accidents to determine the characteristics of a car AEB. However, only few analysis were realized for FCW for bicycle accident scenarios.

Zhao et al. (2019a) analyzed AEB effectiveness based on accident reconstructions from video recorder on taxi-to-cyclist. They found that FOV parameter has a significant influence on collision avoidance. Even with an ideal AEB detection system, i.e. 360° detection angle, some collisions were unavoidable due to cyclists' sudden appearance in front of cars. Lenard et al. (2018) analyzed the FOV values for a pedestrian and cyclist AEB on an English database. They found that 90% cyclists were located in ±80° FOV (e.g. a total detection cone of 160° in front of the car) and within 42m far from the car at Time To Collision (TTC) 3s. They also found that for pedestrians a ±20° FOV (e.g. a total detection cone of 40° in front of the car) was required to detect 80% and within 50m far from vehicle at TTC 3s. In a similar way, Hamdane et al. (2015) found that an AEB system with a 35° field of view seems relevant for detection and crash avoidance with pedestrian. Ohlin et al. (2017) also analyzed the combined measure effect on Swedish accident. They estimated that large injury reductions can be gained with the addition of an AEB for pedestrians and cyclists combined to others measures. Kusano and Gabler (2012) also estimated the injury reductions for the combination of three precollision systems for real-world rear-end crashes. Up from 29% to 56% of fatal injured drivers can be reached. Using a different method, Høye et al. (2015) also estimated up to maximum 16% the killed and seriously injured reduction in Norway during the next 20 years.

Jeppsson et al. (2018) proposed and evaluated also the effect of a Vacuum Emergency Braking system for pedestrian safety in addition to an AEB. This system improves vehicle braking deceleration when combined with a pedestrian AEB reducing up to 22% more casualties compared to an only AEB system.

All those presented studies had estimated the benefits of some safety systems. However, not all benefits have been analyzed and evaluated yet. Indeed as shown in Table 3 and Table 4, most evidences for FCW effects concern car-to-car crashes and very little

VRU. Additionally, the effect estimation is not performed on all accident configurations. Thus this shows the lack of knowledge of FCW effect for different VRU and on specific situations.

	A priori		
Authors	Høye et al. 2015	Kusano and Gabler 2012	Jermakian 2011
System	ACC + FCW + AEB; Pedestrian/cyclist warning with AEB	FCW only; FCW + PBA; FCW + PBA+ PB	FCW
Metric	Injury reduction	Casualty reduction	Crash avoidance
Remarks	Based on Delphi study on 41 vehicle safety experts	Rear-end collision	Car-to-car collision
Effectiveness	16% for killed or seriously injured	Up to 50%	Effect on 1.2 million crashes per year on US

ACC: Automatic Cruise Control

PBA: Precrash brake assist

PB: Autonomous precrash brake

Table 3: A priori estimation of FCW effects

	A posteriori	
Authors	Lubbe and Kullgren 2015	Forkenbrock et al. 2011
System	AEB; FCW	FCW
Metric	Casualty cost reduction	Collision avoidance Response time
Remarks	Five pedestrian crossing configurations; Early and late systems activation; Two different FCW signals; Simulation for driving speed up to 140 km/h	Car-to-car crashes; Analysis on commercial systems; 8 different FCW alert signals
Effectiveness	25% for AEB No effect to 25% for FCW	Crashes in still 53% for the best FCW alert; Crash avoidance reactions: from 270 to 870ms Crash with likely reactions: 330 ms to 1s Crash with not likely response: 870 ms to 1.74s

Table 4: A posteriori estimation of FCW effects

1.3.4 Assessment protocols

AEB were first developed and introduced in safety rating in 2014 to address rear-end car-to-car crashes. Then it has been extended later to address crashes with pedestrians in 2015 and more recently for cyclists in 2018. Since the combination of AEB and FCW can increase road safety effectiveness, the European Commission has decided in 2017 to render mandatory some safety features for new car models like advanced emergency braking or vulnerable road user detection and warning for trucks and buses (European Commission 2018).

Before rendering those safety systems mandatory, test protocols have introduced the evaluation of some of them. Indeed, the European New Car Assessment Program (Euro NCAP) a consumer organization has integrated the testing of those systems in the car's evaluation. Starting in 2013, AEB and FCW were assessed for car-to-car collision (Euro NCAP 2013). Then little by little, evaluations integrated a scoring system (Euro NCAP 2017a; Euro NCAP 2019a) and test scenarios towards pedestrians and cyclists. Concerning scenarios, it can be noticed that all scenarios were not addressed. At first, different crossing scenarios were evaluated for pedestrians with or without visual occlusion before the impact. It concerned adult or child pedestrians crossing from the closest (nearside) or far (farside) side of the road. Later a longitudinal scenario has been added. Recently in 2019, turning scenarios were added in the evaluation for pedestrian AEB with consideration for a car turning to the left or to the right (Euro NCAP 2019b). For cyclists, scenarios addressed were crossing and longitudinal for cyclist AEB (Euro NCAP 2017b). The missing scenarios that have currently not being addressed by Euro NCAP at the time of the writing of this document are: a collision with a cyclist during a car turning left and right manoeuver whatever the origin of the cyclist. With AEB scenario evaluation updates, the scoring system has also been updated. Contrary to the AEB system which has been integrated into many different cars' evaluation protocol, the FCW device has been only added for one specific scenario: the longitudinal (Euro NCAP 2018). As the FCW evaluation is only performed on one specific scenario for cyclists, it appears that identifying the other scenarios can help in the correct evaluation of this safety device. Thus identifying the other scenarios where the FCW can be applied will help completing the knowledge about the effect a FCW can have on cyclist general safety. Additionally, it can also be interesting to see FCW effects for pedestrian safety which can complete and be combined with AEB.

1.4 Research questions

1.4.1 Aim and objectives

The main objective of this thesis is to estimate the benefits of FCW system for different VRU (pedestrian and cyclist) according to different accident configurations based on real-world accident reconstructions. Additionally, a benefit comparison will be given between the different VRU. To that end, some intermediate research questions will be considered to reach the global aim of this work. The first part concerns scenarios and the identification of an AEB characteristic. The second focuses on driver's reaction in different scenarios and per VRU. The final part is the simulation of FCW effect on real world accidents that will lead to the benefit estimation of the FCW system per scenario and per VRU.

1) The first objective of this thesis is to determine which scenarios are challenging and their issues for the pedestrians and the cyclists so as a first step, a work on scenario will be presented. The different scenarios will be identified and real world accidents from our databases will be then classified into those scenarios. After the accident cases classification, a work on AEB is necessary. Indeed in the case of an AEB, this is an automatic system that will automatically initiate a braking manoeuver at the latest time in order to avoid a collision. In the case of a FCW, the braking manoeuver is initiated by the driver after a warning is given to him/her by the FCW. Thus, it appears necessary to determine based on the AEB system trigger time, when to trigger an FCW with consideration of the driver's reaction time. The trigger of FCW should then happen earlier than the AEB trigger time combined with the driver's reaction time to still be able to avoid the collision. So the identification of challenges and issues for an AEB characteristics appears also important. Some elements like FOV, range, visibility time prior the last time to initiate a braking will be studied. It will also illustrate the potential challenges and issues depending on the scenario and the VRU. Additionally, this analysis is a support in the FCW characteristic value choice during the benefit estimation in chapter 4.
2) The next step concerns the human factor which is the driver's reaction. Contrary to an AEB which is an automatic system, the driver is considered as in the center of the loop as he is responsible of the initiation of the emergency manoeuver. Thus it appears mandatory to analyze and understand drivers' reaction towards FCW. This is the second objective of the thesis. To perform this work an experiment on a driving simulator will be presented. The scenario characteristics are extracted from the previous first step allowing to reproduce them on a driving simulator. Drivers' reaction towards FCW on specific scenarios with specific VRU will be then gathered and analyzed. This part will allow to better understand the driver's behavior for different scenarios and VRU in terms of time reaction, the difficulty to manage the situation, the feedbacks towards the presented FCW system, etc.
3) The third and last objective of this PhD is to evaluate the benefit of the FCW on real accident cases. This work will be based on the simulation of FCW system on real-world accident cases. So a simulation method will be proposed to integrate the effect of a FCW system in the kinematic of reconstructed accident cases. The assumptions used in the kinematic simulations will come from the two previous steps of the thesis. The analysis will be performed on different scenarios and on different VRU revealing the similarities and differences between scenarios and/or VRU. Through the variation of different parameters (FOV, FCW signal trigger time and the driver's reaction), a first insight can be given on the potential benefits depending on the combination of those parameters (avoidance, mitigation or no effect). Additionally, results also indicate parameter order influence on the avoidance rates.

1.4.2 Thesis outline

This Chapter 1 aimed at detail the context of the research work and the objectives. As it was explained, three main questions have motivated this thesis.

So, the three following chapters will develop the work performed in order to answer to these three main questions.

Chapter 2 will try to answer the question about the challenges and issues concerning the pedestrian and cyclist accidentology. In this way, investigations on in-depth accident crash cases from Université Gustave Eiffel/LMA and PCM from GIDAS databases will be presented with a kinematic reconstruction of accidents. More than 1500 pedestrian accidents and more than 2000 cyclist accidents will be analyzed and studied. Based on the accident kinematic reconstructions, accident scenarios can be extracted and then classified into the previously identified scenarios. With each accident classified into one scenario, extracting system requirement for each scenario can be determined. Most critical scenarios emerge in terms of detection rate for the FOV and range parameter. Depending on the detection system, the active safety device cannot be triggered if the VRU is not inside the detection cone. Some specificities between pedestrian and cyclist accidents will be highlighted.

Chapter 3 will be focused on the Drivers' reaction to a FCW and it is one of the objectives of the driving simulator studies that will be presented in this thesis. Based on a campaign performed on 200 volunteers, different conditions including in particular several scenarios and several FCW triggering will be tested on driving simulator. This part will describe first the simulator environment and the development to reproduce certain scenarios and FCW. Then, for each configuration, the driver's behaviors are analyzed in particular in terms of time reaction. Again, pedestrian and cyclist configurations are considered in this work.

Chapter 4 concerns the benefits evaluation of a FCW in our accident panel. A simulation software has been developed in order to simulate the kinematic accidents with the addition of the FCW device. With that simulation tool, a parametric analysis has been performed in order to determine the benefits a FCW can reach in terms of crash avoidance or mitigation. Among the different parameters that can be modified as an input in the software, our study will concern the detection FOV and ranges, FCW trigger time, driver's reaction delay or also the choice of the braking model. Effect on speed can also been extracted from the simulation tool. General results and results per scenario will be presented. Differences or similitudes between pedestrians or cyclists' cases will be also highlighted.

A final section will summarize the main results of this thesis and present the future perspective.

2. Accident analysis and challenges for AEB

2.1 Database description

In order to determine accident issues and challenges, the first step consists of accident data collection performed by in-depth investigation team. Their role consists of gathering the maximum data directly on the crash scene in order to determine and establish with the highest precision possible the progress of the accident. So we have decided to base our work on two in-depth accident databases: the "Etudes Détaillées d'Accidents" (EDA) from Université Gustave Eiffel/LMA (Ferrandez et al. 1995) and the "PreCrash Matrix (PCM)" from GIDAS (Schubert et al. 2012).

2.1.1 In-depth accident investigations

The investigation method for French and German is described in Lechner and Ferrandez (1990) and in GIDAS (2020). Each accident is investigated by a multidisciplinary team. They intervene in real time alerted by the rescue team intervention directly on the accident scene. The main interest of quick intervention is based on evidence collection. Directly on scene, the investigation team is able to collect temporary evidences that might disappear or be altered. As an example, illumination conditions during the accident may change due to a fast changing weather or some evidences may disappear due to the rain. Thus, quick intervention is strongly required in order to collect the most accurate and the more data. Data relative to vehicles and the environment like vehicles final position, impact traces (deformation, impact location), marks left on the road (tyres, fluids, debris, etc.), weather and visibility conditions are gathered. Infrastructures data like street geometry, infrastructures, surrounding objects are collected as the environment may also have played a role resulting in an accident. Driver statements and witnesses are also collected. Performed by a psychologist, interviews are helpful to determine participant state during the accident and also before reaching to the accident situation. This part brings human factor explanations in the accident process that might help in the understanding of the accident occurrence from participant's point of view. Finally, injuries and medical reports are also useful as they can help to understand accident progress and also to help improving or evaluating safety features. With a temporal monitoring, it is also possible to determine post-accident effect to analyze long-term consequences.

With the collected data, a kinematic reconstruction of the accident is performed. Hypothesis of the accident mechanisms are made based on trajectories of the involved, displacement speed, emergency manoeuver. Thus, the scenario with the best correlation with all indications produced by the in-depth analysis is chosen.

2.1.2 Université Gustave Eiffel/LMA EDA

The Laboratory of accident mechanism analysis ("Laboratoire Mécanismes d'Accidents" – LMA) is a research unit of the Université Gustave Eiffel. Inside this unit, there is an investigation team called EDA ("Etudes Détaillées d'Accidents") which is involved in accident investigations since the 1980s with around 1300 cases investigated up to 2020.

The investigation team is composed of a technician specialized in infrastructure and vehicles and of a psychologist. Their intervention on crash site usually happens within 15 min after being notified of a crash. This way, evidences can be collected with more precision and before it vanishes like skid marks, debris and any other elements that can be altered. Pictures and movies of the crash site are realized helping later in accident reconstruction and understanding. From the psychologist side, interviews are realized directly on crash site with the involved and witnesses. This first interview is used to collect immediate memories of the accident events from participants' point of view as they remain fresh. After a first pre-analysis to understand and reconstruct the accident, an additional investigation is performed to deepen the assumption extracted from the pre-analysis in order to confirm or invalidate the hypothesis. The last step is the reconstruction of the accident with a final synthesis of the accident progress. Trajectories of the car and VRU are extracted and drawn on a reduced scale map using their initial and final positions. Objects in the surrounding that could affect visibility are also added to the scene. Using displacement speeds and manoeuvers, a temporal reconstruction is performed based on Lechner and Ferrandez (1990) and Lechner et al. (1986) method. In their method, some assumptions are made:

- Constant displacement speed for the car and VRU if there was no brakes activation.
- Constant deceleration is considered.
- A deceleration value is adjusted according to road or brake conditions or to the weather defined by experts.

2.1.3 GIDAS-PCM

The German In-Depth Accident Study (GIDAS) is a database created in 1999 in Germany for the study of in-depth accident (GIDAS 2020). It results from the cooperation between the Federal Highway Research Institute (BASt) and the German Association for Research in the Automotive Technology (FAT). Data collection comes from the region of Hannover and Dresden. The investigation method is similar to the one described previously for French EDA. A multidisciplinary team intervenes to collect data relative to the car, environment and participants if there is at least one injured person. Vehicle deformations and damages or also car's settings are collected. Visibility conditions are investigated as infrastructure geometry or traffic control. Participants' general data like gender, age, driving license are gathered with also medical information with their agreement for long-term consequence analysis. An interview is also performed to get participants' view about the accident. All collected data feeds GIDAS database.

The Pre-Crash-Matrix (PCM) database is extracted from GIDAS. It contains the results of the simulation pre-crash scenario from GIDAS digital sketch through a simulation model developed by VUFO GmbH (Schubert et al. 2012). The version used is 160818_GIDAS_PCM_4.0_2016_1.

2.1.4 Data sample

This research aims at evaluating the benefits of a FCW for pedestrian and cyclist safety. The data samples in this research come from two databases: EDA from Université Gustave Eiffel - LMA and GIDAS-PCM version 160818_GIDAS_PCM_4.0_2016_1 and are summarized in Table 5.

	Université Gustave Eiffel /LMA EDA	GIDAS-PCM	Total
Pedestrian	50	1459	1509
Cyclist	30	2231	2261

Table 5: Accident case numbers extracted from the databases

GIDAS accident cases can be representative of German accidentology using weighting factors. Nevertheless, the PCM database extracted from GIDAS is not representative of Germany due to the case selection criteria. On the other hand, accident cases from EDA are also not representative of France accidentology due to their small size. It has been decided then to combine all data, one for each VRU type and to make analysis considering all the available data.

2.1.5 Accident kinematic reconstruction

This section describes the accident kinematic reconstruction method used for French EDA cases. A similar method is used for German PCM data (Schubert et al. 2012). Figure 11 illustrates the different steps to perform the kinematic reconstruction of an accident. This reconstruction step is necessary in order to extract data that will be used as input in the software simulation with the introduction of FCW effect.

- Step 1: the reconstruction starts from a reduced map scale of the accident where the map scale is read (red circle).
- Step 2: the car and VRU trajectories are drawn on the map (respectively in blue and red in the figure). It requires at least two positions: an approach and the impact positions. Two points correspond to one portion to which a particular kinematic will be applied (rectilinear uniform motion, accelerated or decelerated rectilinear

motion). A decelerated portion can correspond to a braking initiated by the driver. For more portions, different kinematic can be applied for each portions (step 3).

- Step 3: For each involved in the accident (car and VRU), different parameters are required to extract kinematic values. For each portion, a deceleration value, the speed at the beginning and the end of the portion, the initial and final position of the portion, the travel time, the speed variation or the travel distance are asked. Not all the previous parameters are required as some can be computed.
- Step 4: Elements of the surroundings environment which can be responsible of occlusion are drawn on the map (drawn in black on the figure). This step might be optional if no object hides the VRU.
- Step 5: The results of the reconstruction is finally obtained. This reconstruction process returns the positions of the car and the VRU, the instant speeds with the corresponding time to collision (TTC) at a frequency of 100 Hz. It also returns the position of the static objects responsible of occlusion. All those data will serve as input in the FCW simulation software.

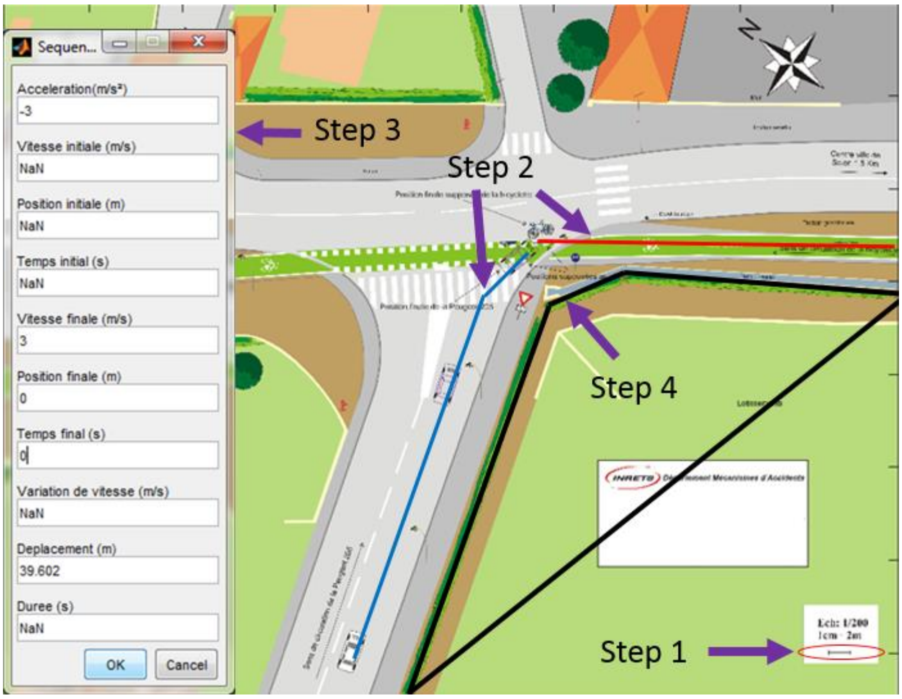


Figure 11: Accident kinematic reconstruction method

2.2 Tools development

In order to make an estimation of FCW benefit for pedestrian and cyclist safety, simulation tools have been developed. Those tools enable to integrate an AEB or a FCW in accident cases from our two databases and to determine their final outcomes. The introduction of AEB at first serves to determine the challenges and main issues a FCW can encounter. Indeed, the same detection system can be used for both AEB and FCW system. The analysis with the addition of an AEB allows determining when is the Last Time To Brake (LTTB). This value corresponds to a distance in meters required in order to stop the vehicle to avoid the impact with the VRU. By knowing this distance, it is possible to determine the detection rate a system can achieve when the automatic braking system is supposed to be triggered according to two parameters: the FOV and the range. It is also possible to determine how long the system can detect the VRU prior reaching that critical moment. This work which integrates an AEB system was inspired by the work from Hamdane et al. (2015).

To perform a simulation, some data are required like the kinematic of the original accident cases. Positions of the car and the VRU and instant speed at each time step prior the first impact are needed as objects in the surrounding environment responsible of occlusion. The consideration of occlusion is important as it may lead to a late system triggering. Then, it is necessary to introduce the system parameters as inputs like the detection FOV and range, the deceleration value and also the AEB or the FCW trigger. From there, the simulation software returns a value indicating if the collision has been avoided or not with the new kinematic of the car (positions and speeds). Figure 12 illustrates the general software that has been developed with inputs and outputs details for each module (Figure 13).

However this previous software needs to be adapted in order to integrate the effect of a FCW. Indeed, the FCW system required an additional data: the driver's reaction. In order to simulate properly the effect on a driver, it is necessary to determine how long the driver will react to the FCW warning message. This data will be used to consider the lag duration after the FCW has been triggered to initiate a braking. It is also necessary to determine in the original accident if a braking manoeuver has been initiated and when. This information will be useful to determine if the FCW trigger will introduce or not a braking from the driver based on the combination of FCW trigger time and driver's reaction. If the driver braked earlier in the original accident compared to the FCW trigger with the driver's reaction time, then it will be considered that the FCW will have no effect.

The simulation software initially designed for pedestrian accident cases has been adapted for cyclist accident cases and has also been adapted to the PCM database.

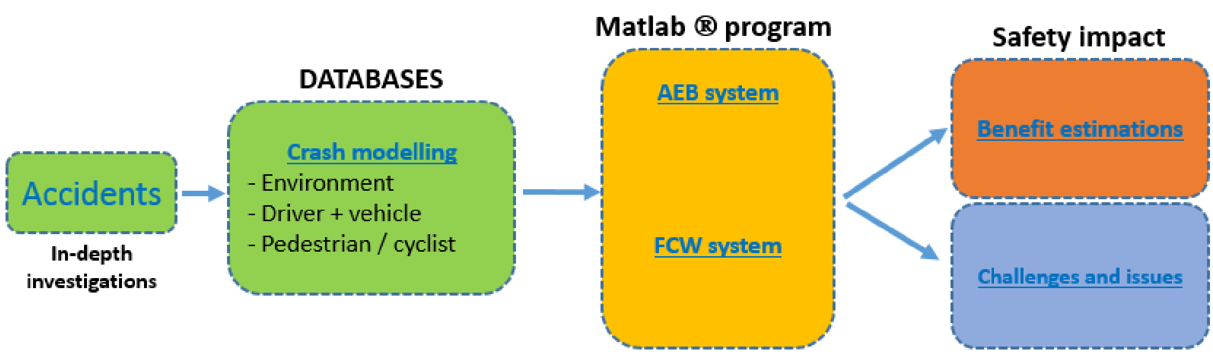


Figure 12: Global software development

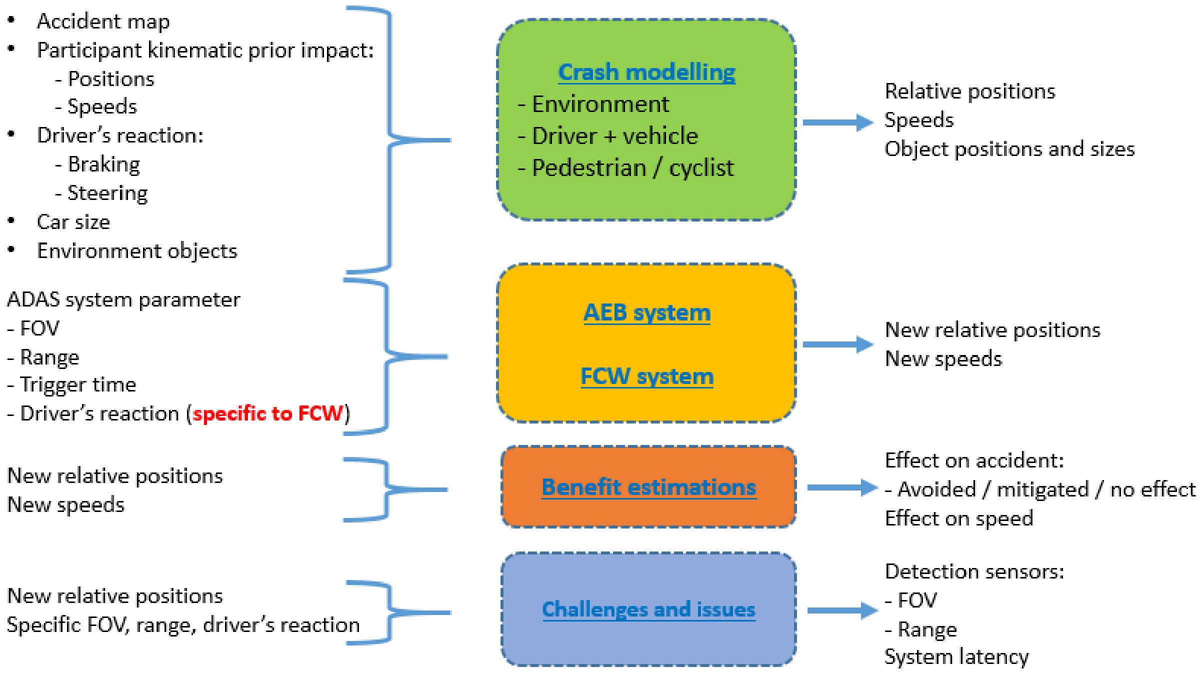


Figure 13: Inputs and outputs of the different software modules

2.3 Analyzed parameters

As it has been shown above, several parameters appear as important to be analyzed. Among them, we focused our research particularly on the influences of scenarios. So, we will first detail in this section, the choices made to determine the scenarios.

Then, from the accident kinematic reconstructions, it is possible to determine the requirement for detection sensors for an AEB system. In this section, an analysis of the FOV and the distance range is given in order to determine the appropriate values to detect VRU. After detecting the VRU, it is also necessary to determine the distance required in order to stop the car depending on the braking system. This way, the stopping distance called Last Time To Brake (LTTB) is analyzed which also gives the time to stop the car (t_{LTTB}). Required also for AEB and FCW, the visibility duration before the car reaches the LTTB is important. If we go back in time from the t_{LTTB}, this duration can correspond for an AEB to the time required for data processing and decision making. On contrary for a FCW, this duration can correspond to a driver time reaction after a signal is emitted prior reaching the t_{LTTB}. As this parameter can be useful for both devices, this parameter is also analyzed.

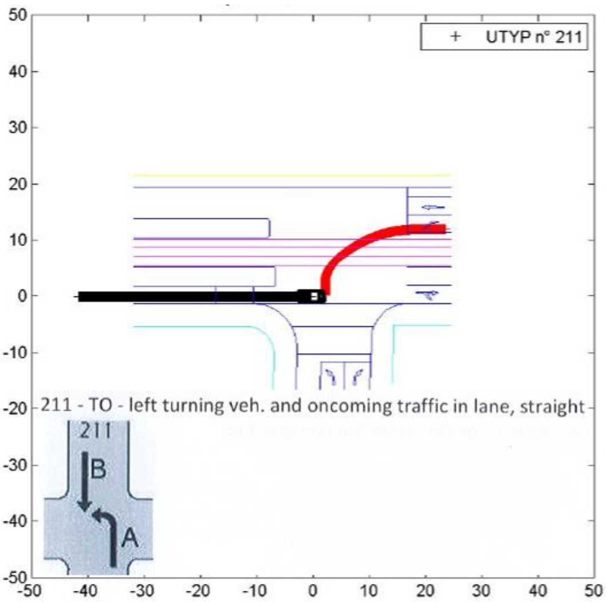
2.3.1 Accident scenario

2.3.1.2 Accident classification

As this research aims to evaluate the benefits of a FCW, some choice has been done concerning the accident classification category of the accident scenarios.

It is interesting to mention here that a classification method exist based on pictograms: small schematic representing the accident (Uittenbogaard et al. 2016a). In GIDAS database, each accident (except for some oldest cases which have not been coded) has a UTYP pictogram. This pictogram corresponds to those that can be found in the catalogue of HUK from 1977 as mentioned in the GIDAS codebook (VUFO GmbH 2016b). However as indicated in the GIDAS codebook, the pictogram describes the situation or the conflict situation that led to the accident. Thus, the UTYP might not correspond to the real accident configuration. Moreover Ranjbar (2014) made a comparison between UTYP pictograms and a geometrical classification based on the dynamics of the accident participants. He found that the geometrical classification was more accurate compared to the UTYP pictograms. Indeed, the UTYP pictogram cover most but not all accident configurations. This lead some accident cases to be coded with a UTYP that may not be appropriate. Additionally, there are some coding errors. During a quick review, we also noted that one UTYP pictogram can be associated to very different configurations illustrated by Figure 14. In the figure, the car and the cyclist kinematics are drawn in black and red. Both accidents have the same UTYP 211. On the one hand, the car collide a cyclist during a turning left manoeuver, on the other hand a collision happened when the car was going straight. For this research, the focus has been set on the FCW system which can be assimilated as the car point of view. Thus this example clearly illustrates that a classification based only on the UTYP is not suitable for this research. Our observation is not quantified and Ranjbar's analysis was done on 1365 GIDAS-PCM cases. However it could be interesting to determine precisely the UTYP precision or error.

It can be noticed that other classification methods exist like in Lara et al. (2019) and Lubbe et al. (2018). However, as the classification work in this thesis has been done prior those publications. Thus, those methodologies have not been taken into account.



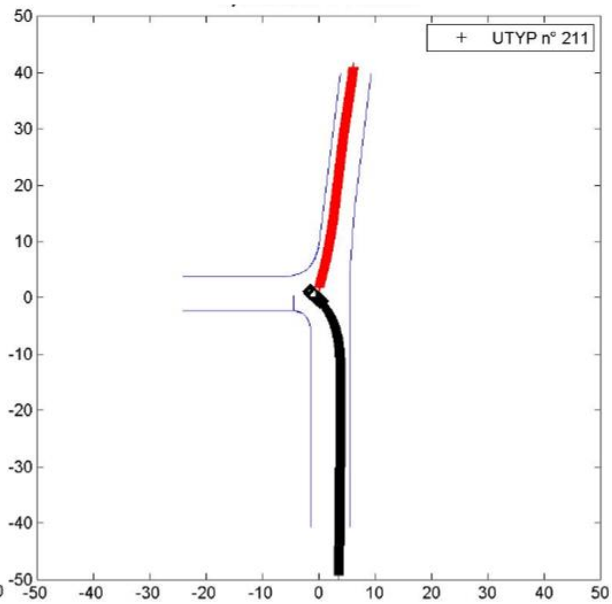


Figure 14 : Illustration of UTYP coding for two different cases

In this work, UTYP has not been considered as it may describe a conflict leading to a collision which may not correspond to the course of events. This is why, we work on finding our own classification criteria based on the point of view of the car active safety system. Thus, it has been decided to consider car and cyclist trajectories and also infrastructure to identify scenarios. From previous researches and projects, scenarios kept are common ones that are regularly found either for pedestrians and cyclists. In total, 5 scenarios have been considered: two crossings (nearside and farside), two turnings (right and left) and one longitudinal scenario. Among the criteria used for classification, VRU trajectory intervenes to distinguish if an accident is a crossing nearside, a crossing farside or a longitudinal. The infrastructure intervenes to separate crossing from turning and from longitudinal. More detailed explanations are given after the scenario descriptions. Below is the description of the five chosen scenarios:

- Crossing Nearside scenario (CN): the vehicle drives straight and a pedestrian/cyclist crosses from the closest side of the road (On a 1 way road, a pedestrian/cyclist crossing from the left or the right is also considered as a CN).

- Crossing Farside scenario (CF): the vehicle drives straight and a pedestrian/cyclist crosses at least one lane of road before being hit by the vehicle.

- Longitudinal scenario (L): the vehicle and the pedestrian/cyclist both travel in the same direction on the road, and the car hits the pedestrian/cyclist in the rear during the travel or laterally during an overtaking manoeuver.

- Turning Left (TL) or Turning Right scenario (TR): the vehicle is turning left or right at an intersection and hits a pedestrian/cyclist whatever the trajectory of the cyclist. Situations where the vehicle is outside an intersection are excluded from this cluster.

Cases where a vehicle follows a curve to the right (or to the left) and a pedestrian/cyclist crosses the road are clustered either in CN or CF scenario. Cases where a vehicle is in a curve and encounters a pedestrian/cyclist travelling in the same direction are clustered in the L scenario.

- Other scenarios: all accidents where the impact occurs at the rear of the vehicle or that could not be cluster in any of above scenarios.

Figure 15 illustrates the previously described scenarios.

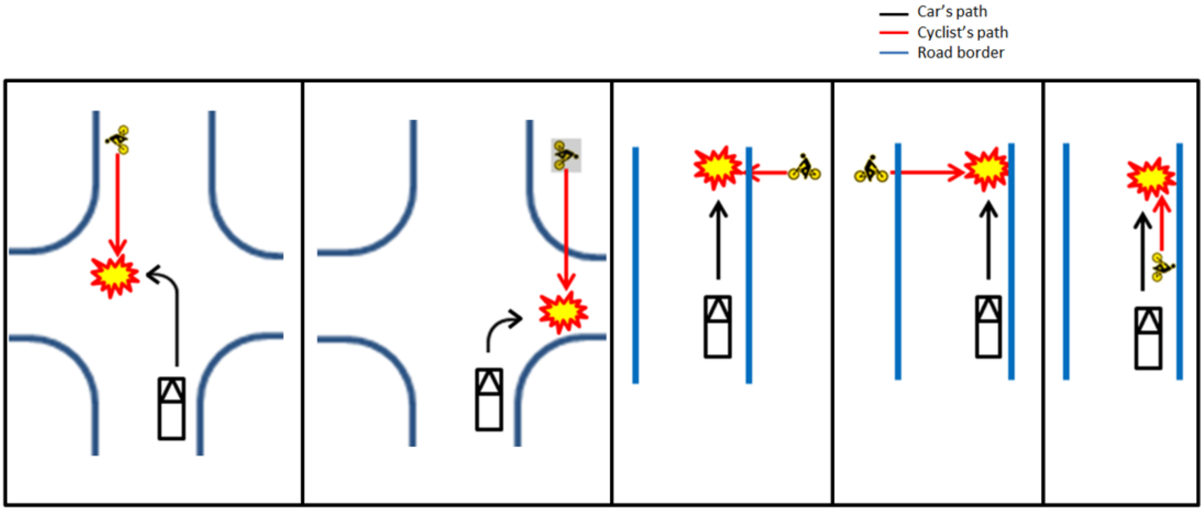


Figure 15: Chosen scenarios for accident classification, from left to right: turning left; turning right; crossing nearside; crossing farside and longitudinal

From this general scenario description comes next accident classification into one of these categories. Classifying accident cases appears to be trivial but is a very complex task. At first, drawing accident sketches is necessary. From Université Gustave Eiffel/LMA, accident sketches are already drawn and can be visualized. From GIDAS/PCM, accident sketches need first to be drawn from the database using car and VRU positions, road infrastructures and marks and also the surrounding environment like building, tree or any objects that may play a role in the accident. From these sketches, each accident is classified individually into one of the previous scenarios.

To decide into which scenarios an accident is classified, some questions can help in the decision making. At first, the kinematic of the car and the VRU have to be known otherwise, the accident is classified into the "Others" scenario. If no kinematic trajectories are missing, the next step is to determine if the impact happens in the rear of the car. If it is the case, then the accident is also placed into the "Others scenario". From there intervene car's trajectory into the classification decision making. If the car is at an intersection and is turning, then the case is classify as a turning right (respectively left) if the car is turning to the right (respectively turning to the left). Otherwise, if the car is at an intersection but is not turning then additional questions are required to distinguish crossing nearside, crossing farside and longitudinal. If the car is going straight and if the VRU is also going straight in the same direction as the car, then the accident is classified as a longitudinal scenario. In the case the VRU is going straight but from the opposite direction, then the case is classified into the “Other” scenario. If the VRU is crossing the road, then the origin of the VRU is taken into account to classify the accident into crossing nearside or crossing farside. Figure 16 illustrates the decision making for accident classification.

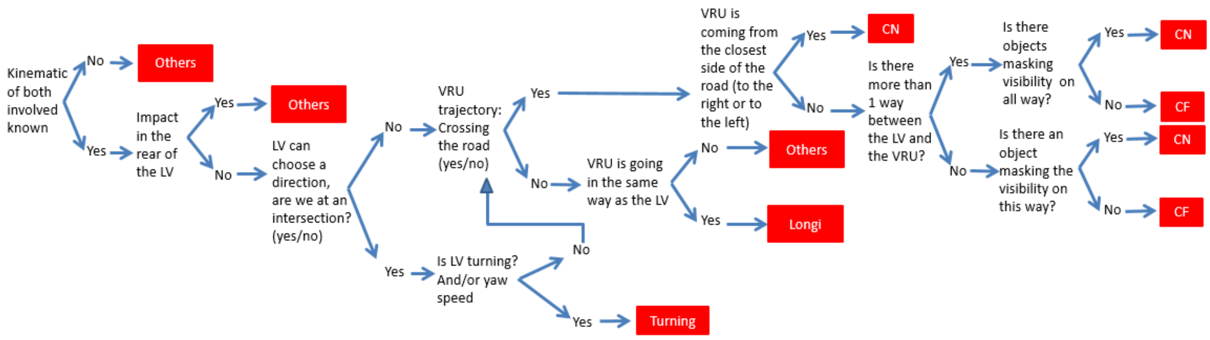


Figure 16: Decision tree used to classify accident into one of the five accident scenarios or in the “Others” group

This qualitative and manually procedure based on Figure 16 to classify accidents has been chosen instead of an automatic classification based on threshold criteria. The criteria choice and also the associated threshold values are difficult to find. Indeed, these values can be strongly dependent on the chosen sample for threshold extraction and can be also sensitive to the accident cases. Let’s take as an example two turning right accident, one in a Y-junction and the other one in a cross-junction. If the criterion to decide that the car is making a turning manoeuver is the yaw angle, then if the car is coming from the bottom branch of the Y-junction, that value will be lower compared to the cross-junction. Moreover, the location of the impact during the displacement of the car can also influence the scenario classification. A collision that happens at the very beginning or at the end of a turning manoeuver will be different from a quantitative point of view. This way depending on the sample where the criteria value has been established, a case where a car is turning in a Y-junction can be incorrectly classified not as a turning. This is one example but there are many others that can illustrate the difficulty to realize an automatic and correct classification based only on this method. As each accident is unique by car and VRU’s trajectories and also by the infrastructure where the accident takes place, a threshold is sometimes required. Let’s take as an example a car going straight and a VRU crossing but in an oblique way. In this case, the angle between car and the VRU trajectory will be considered to distinguish if the case is a crossing or a longitudinal.

Figure 17 illustrates cases where the decision making is difficult. The position of the car is drawn in black and the position of the VRU is drawn in red. Infrastructure is drawn in blue and objects of the surrounding are drawn in green. The center part of Figure 17 ideally illustrates a case where the angle between car and the VRU trajectories will help determining in which scenario this accident will be classified. Thanks to the angle formed between car and VRU trajectories, the case has been classified into the longitudinal scenario and not as a crossing. The right part of Figure 17 is another illustration of the classification difficulties. On this case, general trajectories of the car and the VRU appear to go in the same direction except at the end of the car's trajectory which is more curvilinear. Based on general trajectories, the case could be classified as a longitudinal. Indeed, the car may overtake and hit the VRU during this manoeuver. However, the infrastructure shows an intersection and the possibility for the car to turn to the right. As the car's trajectory is a curve orientated on the right side, it supports the hypothesis that the car is turning to the right. Thus, this case is classified as a turning right instead of a longitudinal. Last but not least, there is the case of the left part of Figure 17. On this case, a car is going straight and a VRU is crossing the road between two objects drawn in green. Light blue lines represents pavement limit and dark blue are road marks. Due to car and VRU trajectories, the case will be classified as a crossing, then remains the question to classify it into the nearside or the farside scenario. Let's take into consideration the surrounding objects drawn in green in the accident sketch. The green objects are rectangle objects located on the road. Unfortunately, when looking more precisely into GIDAS-PCM cases, these objects are coded as unknown. They look like cars because their sizes are similar to the one of the black car involved in the crash and because they are on the road. This way, these objects will be considered as cars. With this hypothesis, the classification is not easier. Is the case a crossing farside because the VRU crosses at least one way before reaching the black car's path or is it a nearside due to the car attendance? The answer will be resolved through one another criteria: the occlusion. Thanks to this sketch, it appears that cars were parked or were not moving during the configuration. The occlusion criterion is used here as the main difference between farside and nearside is the duration where the VRU can be visible. For farside situation, the VRU takes more time to get into car's path. This is why, the current case is classified as a crossing nearside. Moreover, this case is similar to a scenario that can be found in Euro NCAP test protocol (Euro NCAP 2015). Indeed, the test protocol proposed a scenario with a running child that crosses the road in a similar way. This scenario was considered as a crossing nearside by Euro NCAP. That is why in the decision making tree, an additional question can be found if the VRU has to cross more than 1 way before reaching car's path. This question is related to the occlusion parameter and allows making the distinction between crossing nearside and farside.

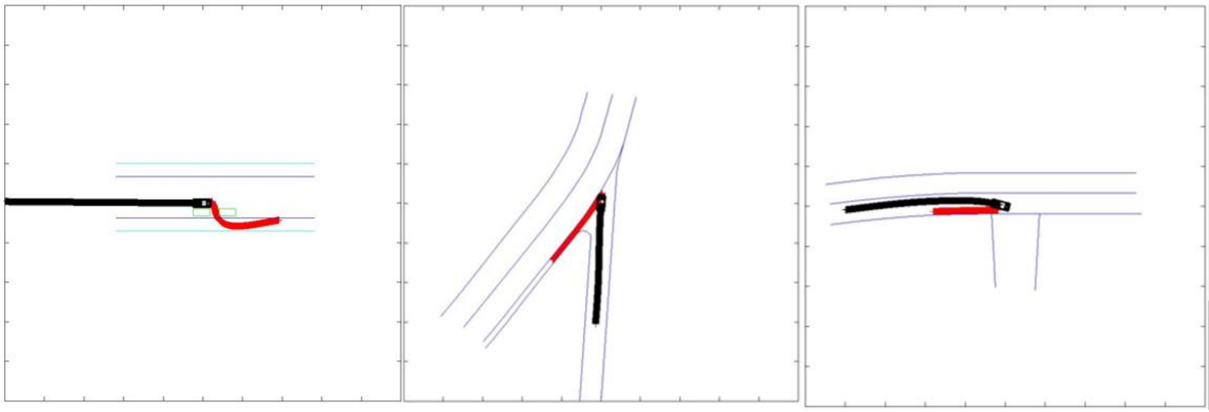


Figure 17: Illustration of accident cases that are difficult to classify. The accident classification results for those three cases are (from left to right): crossing nearside; longitudinal; turning right)

2.3.2 AEB characteristics

In order to determine the appropriate detection parameter an AEB system should have, it is necessary to analyze the required FOV and range for car's sensors. Car's sensors positions are modelled at the car's geometrical center in this analysis. This assumption can be subject to discussion as some sensors are located in front of the car (Coelingh et al. 2010; Hayashi et al. 2012; Meinecke et al. 2005; Scheunert et al. 2004). However, when using a camera device for those systems, the camera can be located beside the rear view mirror (Gandhi and Trivedi 2007). This way, it should be acknowledged as a slight increase of the detection cone even if car geometrical center and rear view mirror location are close.

The FOV value Θ will correspond in this work to half of the detection cone formed by half straight line [Ox) and [OM) (see Figure 18). Thus, a FOV of 20° corresponds to a total detection field of 40°. This FOV definition can also be found in Lenard et al. (2018) paper relative to their parameter analysis for an AEB system for pedestrians and cyclists. A pedestrian or a cyclist is considered as detected if his/her center is located inside that detection cone without consideration of the distance to the car (infinite detection range inside the cone). Considered values for the FOV analysis goes from 10° to 70° based on Hamdane et al. (2015) results for pedestrian accidents. In their research, they found that a 35° is required for pedestrian detection for an AEB system. As cyclist travel speed is higher compared to pedestrian as found by Huang et al. (2008), FOV detection values have been extended to 70°.

The range detection is defined as a circle with a radius of ρ around the geometrical center of the car (see Figure 18). Similarly to the FOV, a pedestrian or a cyclist is considered as detected if the pedestrian or cyclist center of gravity is located inside that detection circle. Range values from 5 to 45m have been considered in this study also based on Hamdane et al. (2015) and from the analysis on pedestrian and cyclist relative position to the car. The results of the VRU relative position to the car is given in section 2.4.

Figure 18 illustrates the definition of the FOV detection cone. Section 2.4 gives the analysis results for the FOV and the range parameters.

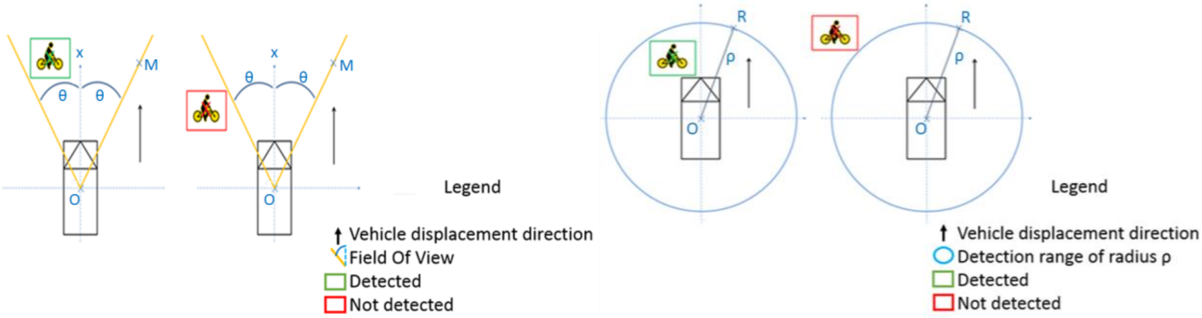


Figure 18: FOV and range sensors modeling

In order to trigger an emergency braking for an AEB, it appears obvious that the system has to detect the VRU prior the collision in order to avoid it. This way, an analysis is performed in order to determine the detection rate for different FOV values at the moment an AEB is supposed to be triggered. The formula used to calculate the stopping distance also called Last Time To Brake (LTTB) is given by the Eq. 1:

$$LTTB = \frac{V^2}{2*|a|} \qquad \text{(Eq. 1)}$$

where V corresponds to the car's travel speed (m/s) and a is the deceleration coefficient (m/s^2). This formula is similar to the one used by Hamdane et al. (2015) and by Violette and Le Bec (2016).

In our analysis, an ideal braking model has been considered with a maximum deceleration value of -8m/s^2. It means that when brakes are applied, there is no transient state and the deceleration reaches directly that maximum value and remains at this maximum value. That deceleration value corresponds to ideal conditions like dry surface, efficient braking system, etc. as it can be found in Brach and Brach (2005), Byatt and Watts (1981) and Lechner and Ferrandez (1990). As this considered braking model is not realistic, a comparison with two other braking models will be performed to determine if detection rates are affected. The two other models have kept the maximum deceleration value with a consideration for a transient state. It means that the deceleration coefficient a increases linearly from the brakes activation until it reaches the maximum value and then remains at this maximum value. Two transient state durations have been considered for comparison with our ideal braking model: 0.15s and 0.3s as it can be found in Zhao et al. (2019b) and in Saadé et al. (2019).

2.3.3 Visibility

As an AEB is supposed to trigger in order to avoid the impact, the system may have some requirements that have to be taken into account before its activation. The system may need time to collect and gather data from the difference sensors of the system, to compute the path of the car and VRU and also time for the decision making to trigger or not the brakes. This way, it appears important to determine the amount of time available before reaching the LTTB. As the LTTB represents a distance in meter, the value t_{LTTB} corresponds to the LTTB information but in second. The duration tvisible-t_{LTTB} is the duration from the first time the VRU is not occluded to the t_{LTTB}. It can indicate the visibility amount of time before the t_{LTTB} but it can also represent a late delay. Indeed, in the case the VRU is occluded at the t_{LTTB}, the VRU will be detected after the t_{LTTB} which means that the accident cannot be avoided. In summary, when the duration tvisible-t_{LTTB} is positive, it means that the VRU can be detected prior reaching the t_{LTTB}. The value tvisible-t_{LTTB} indicates then that there is tvisible-t_{LTTB} seconds to trigger an AEB if the VRU is inside the detection field. When the duration tvisible-t_{LTTB} is negative, this value indicates that the accident cannot be avoided with an AEB because of activation later than t_{LTTB} due to occlusion. Figure 19 illustrates the described method. On the Figure 19a, the VRU is not occluded at t_{LTTB} and we go backward in time to determine tvisible which is the first time the VRU is inside sensors FOV. The duration tvisible-t_{LTTB} is a positive value and represents the available time before reaching t_{LTTB}. On the right part of Figure 19b, the VRU is hidden by an object at t_{LTTB}. Due to the occlusion, we then continue in time and determine when the VRU will be inside sensors FOV after t_{LTTB}. In this case, the duration tvisible-t_{LTTB} has a negative value and represents the activation delay of an AEB.

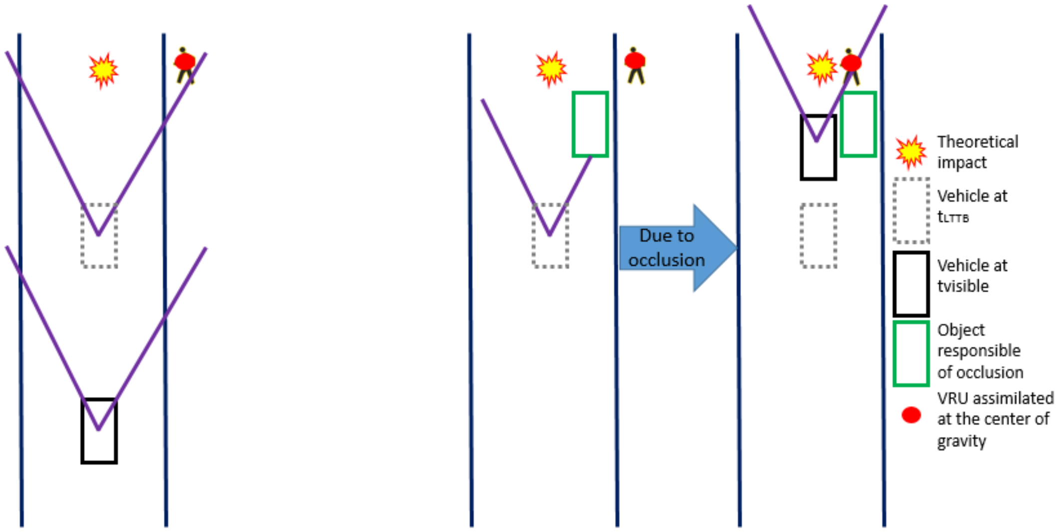


Figure 19: Calculus method of the duration tvisible-t_{LTTB} in two configurations: without occlusion on the left (Figure 19a) and with on the right (Figure 19b).

2.4 Analysis / Challenges / Issues

2.4.1 VRU relative position to the car, driver brake activation, vehicle approach speed and accident clustering

2.4.1.1 Pedestrian accident cases

This section gives the pedestrian relative position to the car, the proportion of brakes activation during accidents and also the results of accident clustering into scenarios. The sample is composed of 1509 accident cases involving one car and one pedestrian. Results are given first for all accident cases, then per scenario.

A visual representation of pedestrian relative positions to the car at different TTC before the impact is given by Figure 20 for all cases of our sample for TTC 2s, 1.5s, 1s, and 0.5s. Most pedestrians are located within 40m ahead the front of the vehicle and less than half of them are ±3m laterally to the car center at TTC=2s. At TTC 1s prior the impact, most pedestrians are located 20m ahead the vehicle front and about 80% of them are inside the ±3m laterally to the car center. At TTC 0.5s, nearly all pedestrians are located within the ±3m laterally to the center of the car and 10m ahead the vehicle. It can be remarked that even 1 or 0.5s prior the impact, the proportion of pedestrians located in front of car's trajectory is low.

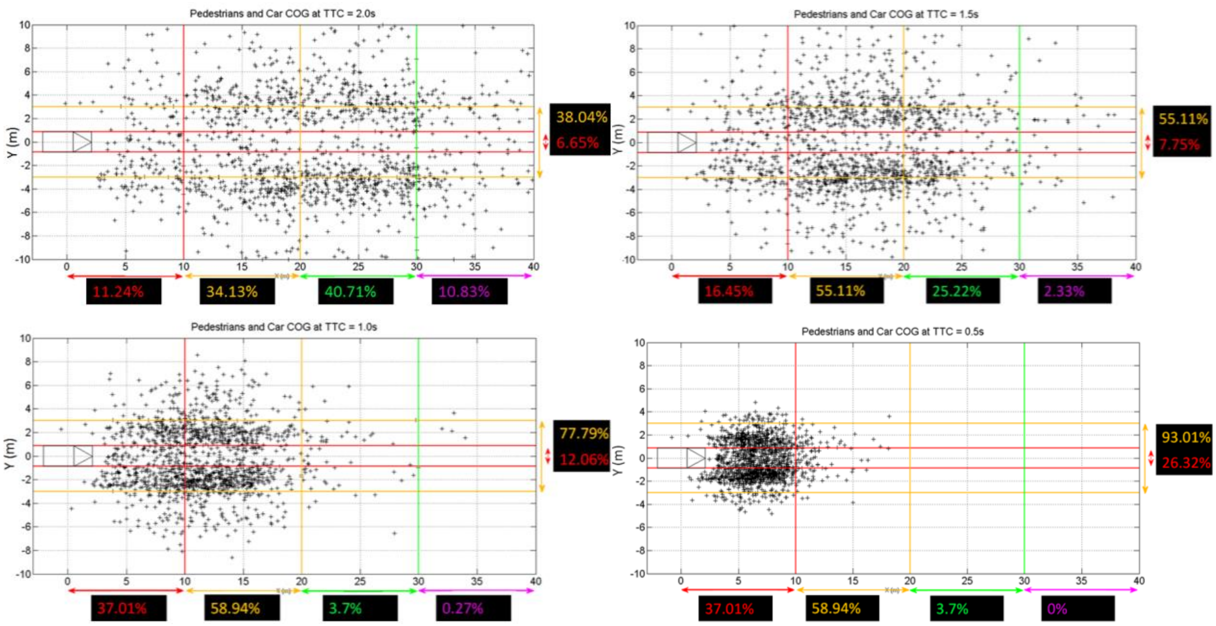


Figure 20: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all accidents of our sample (N = 1509)

Drivers approach speed has been extracted. The approach speed corresponds to the travelling speed of the vehicle before the brakes activation. In the case brakes have not been activated, the approach speed is equal to the speed at the impact. Figure 21 right part gives the car travelling speed for our entire sample. It can be noticed that about 50% drivers were driving below 35km/h and 80% below 50km/h.

The proportion of brakes activation has also been extracted. Among all cases, only 51% of the drivers braked before the collision. The brake trigger took place less than 0.5s prior the impact for 50% of drivers and reached close to 90% brake activation 1s prior the impact. Figure 21 left part shows the cumulative frequency of brakes activation.

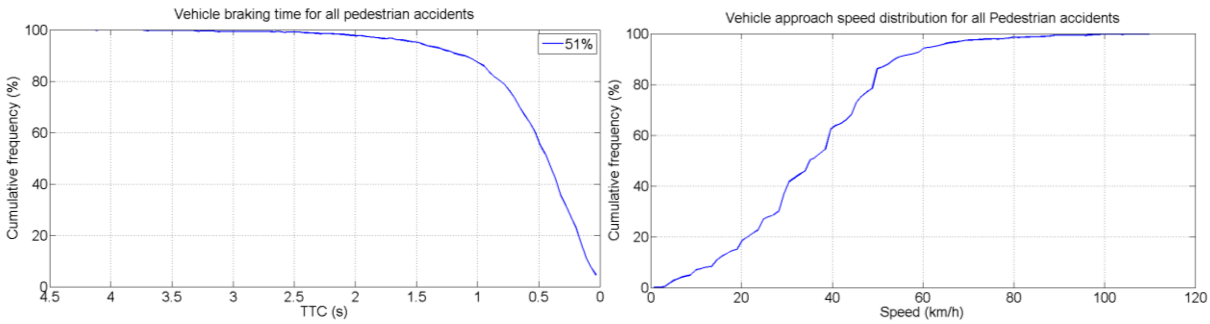


Figure 21: (Left) Cumulative frequency of brake activation timing (51% of all cases) and vehicle approach speed (Right), N = 1509

Based on the accident classification section, accident clustering reveals that our sample is composed in descending order of 52% of CN scenario, 31% of CF scenario, 8% of TL scenario, 4% of TR scenario and 1% of L scenario. The remaining 4% are clustered into the "Others" group as they do not enter into one of the five main identified scenarios. It can be remarked that our sample is composed of a vast majority of crossing configuration.

Results per scenario for the relative position and the brake activation are given below. It provides information about scenario specificities.

Pedestrian Crossing Nearside (P-CN)

Based on the accident classification section, among our 1509 accident cases, 788 of them are clustered into the CN scenario which represents 52% of our sample. Figure 22 gives the pedestrian relative positions to the car for P-CN scenario. From this figure, it can be noticed that in this configuration, there are more pedestrians coming from the right side of the car. This might be explained by the fact that cars drive on the right in Germany and in France. At TTC 2s prior the impact, pedestrians are located within a 40m ahead the car front and only a few of them are already inside car's direct trajectory. At TTC 1s and 0.5s, pedestrians are respectively 20m and 10m ahead car's front with still a small proportion inside car's direct path.

The brakes activation extraction reveals that 397 drivers have initiated a braking manoeuver among the 788 CN cases, representing 50% brake activation for this scenario. 90% drivers have initiated brakes 1s prior the collision and 50% brakes activation of those who have triggered brakes have performed it at TTC less than 0.5s. Figure 23 shows the drivers' braking timing among those who have braked for this scenario.

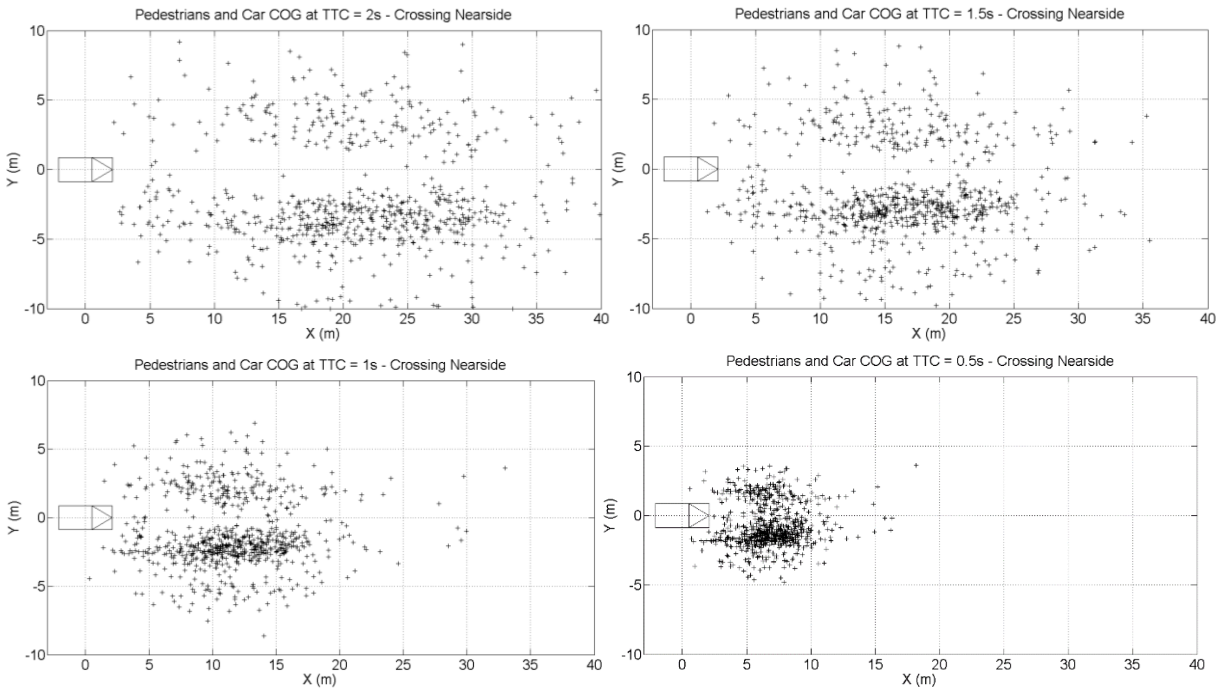


Figure 22: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-CN accidents (N = 788)

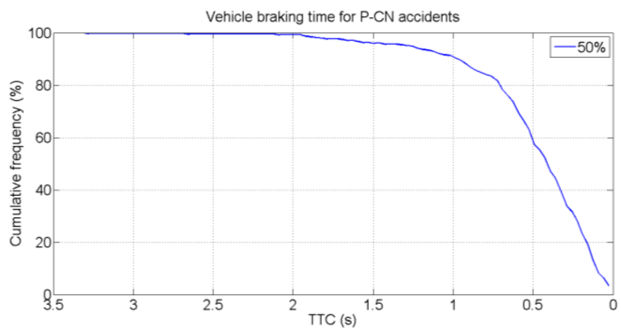


Figure 23: Drivers' braking timing for the P-CN scenario, 50% braking activation among 788 P-CN accident cases

Pedestrian Crossing Farside (P-CF)

Based on the classification section, 461 accidents cases among the 1509 are clustered into the CF scenario which represents 31% of our sample. Figure 24 gives the pedestrian relative positions to the car for P-CF scenario. From this figure, it can be noticed that in this configuration, there are more pedestrians coming from the left side of the car. Based on the definition of this scenario, the pedestrian has to cross at least one way of road before reaching car's path. As cars drive on the right in Germany and in France and as drivers have to keep right when there are multiple way in the same direction, it appears logical that pedestrians are coming from the pavement on the opposite side which is on the left. At TTC 2s prior the impact, pedestrians are located within a 40m ahead the car front and only a few of them are already inside car's direct trajectory. At TTC 1s and 0.5s, pedestrians are respectively 20m and 10m ahead car's front with still a small proportion inside car's direct path.

The brakes activation extraction reveals that 279 drivers have initiated a braking manoeuver among the 461 CF cases, representing 61% brake activation for this scenario. Similarly to P-CN scenario, about 90% drivers have initiated brakes more than 1s prior the collision and 50% have trigger brakes at TTC 0.5s. Figure 25 shows the cumulative braking frequency of brake activation for this scenario.

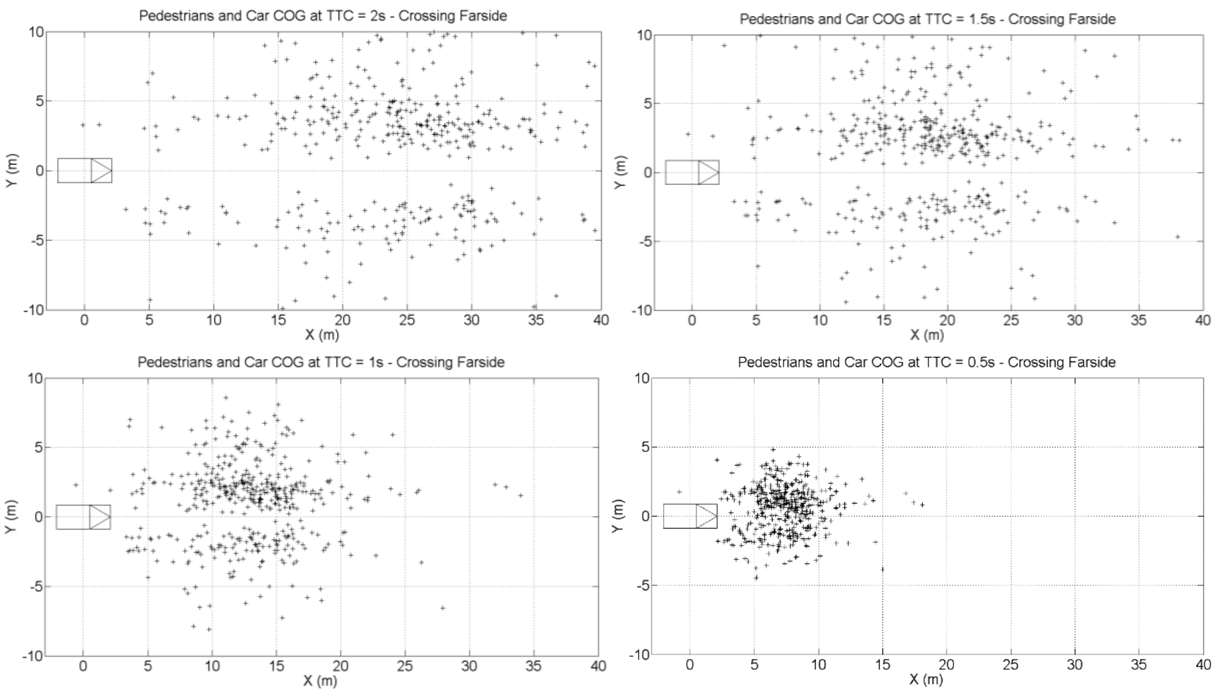


Figure 24: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-CF accidents (N = 461)

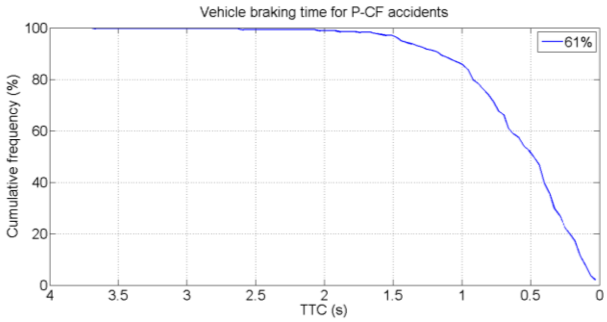


Figure 25: Drivers' braking timing for the P-CF scenario, 61% braking activation among 461 P-CF accident cases

Pedestrian Longitudinal (P-L)

Based on the classification section, 20 accidents among the 1509 are clustered into the L scenario which represents 1% of our sample. Figure 26 gives the pedestrian relative positions to the car for P-L scenario. From this figure, it can be noticed that pedestrians are located 35m ahead the car's front at TTC 2s prior the impact, 25m at TTC 1s and 15m at TTC 0.5s. It can be highlight that all pedestrians are already inside car's direct path 2s prior the impact contrary to what can be observed for the other scenarios. This difference might be caused by the configuration itself. Indeed, a collision in this configuration requires that the pedestrian is on the road when the collision happens. Hence it might explain why pedestrians are already on the road at least 2s prior the impact.

From the brakes activation extraction, 4 drivers have initiated a braking manoeuver among the 20 L cases, representing 20% brake activation for this scenario. Brakes have been triggered less than 0.6s prior to the impact except for one case where brakes have been triggered more than 2s before. Figure 27 shows the cumulative braking frequency of brake activation for this scenario.

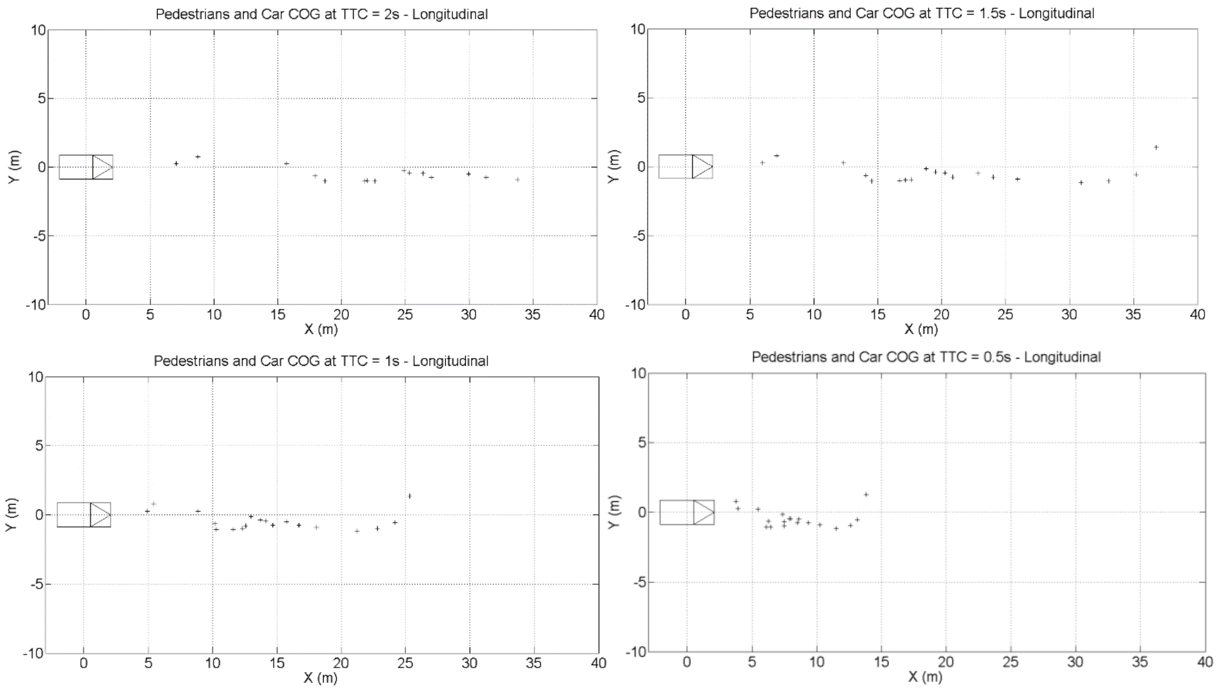


Figure 26: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-L accidents (N = 20)

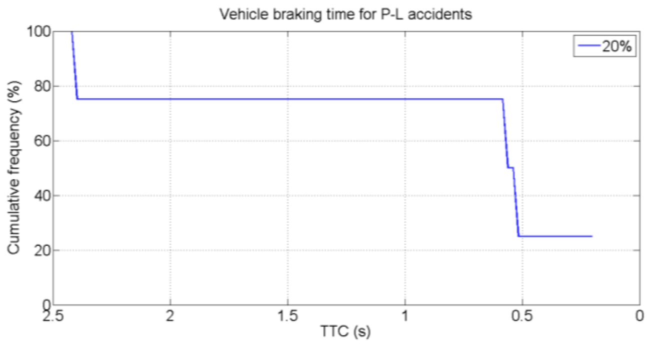


Figure 27: Drivers' braking timing for the P-L scenario, 20% braking activation among 20 P-CF accident cases

Pedestrian Turning Left (P-TL)

Based on the classification section, 124 accidents among the 1509 are clustered into the TL scenario which represents 8% of our sample. Figure 28 gives the pedestrian relative positions to the car for P-TL scenario. At TTC 2s prior the impact, pedestrians are scattered and are located 25m ahead the car's front, 15m at TTC 1s and 10m at TTC 0.5s. Similar to P-CN and P-CF scenario, only a few pedestrian are on car's path a few second before the collision. Contrary to crossing scenarios, readers have to keep in mind that the current representation centered on the car does not reflect the turning manoeuver. Thus depending on the turning style during the accident kinematic, on the infrastructure of the intersection, it appears more difficult to extract information of pedestrian location ahead the car's front. However, it can be noticed that more pedestrians are coming from car's left side during this scenario.

From the brakes activation extraction, 48 drivers have initiated a braking manoeuver among the 124 TL cases, representing 39% brake activation for this scenario. More than 80% drivers have initiated brakes 1s prior the collision and 50% have trigger brakes less than 0.4s. Figure 29 shows the cumulative braking frequency of brake activation for this scenario.

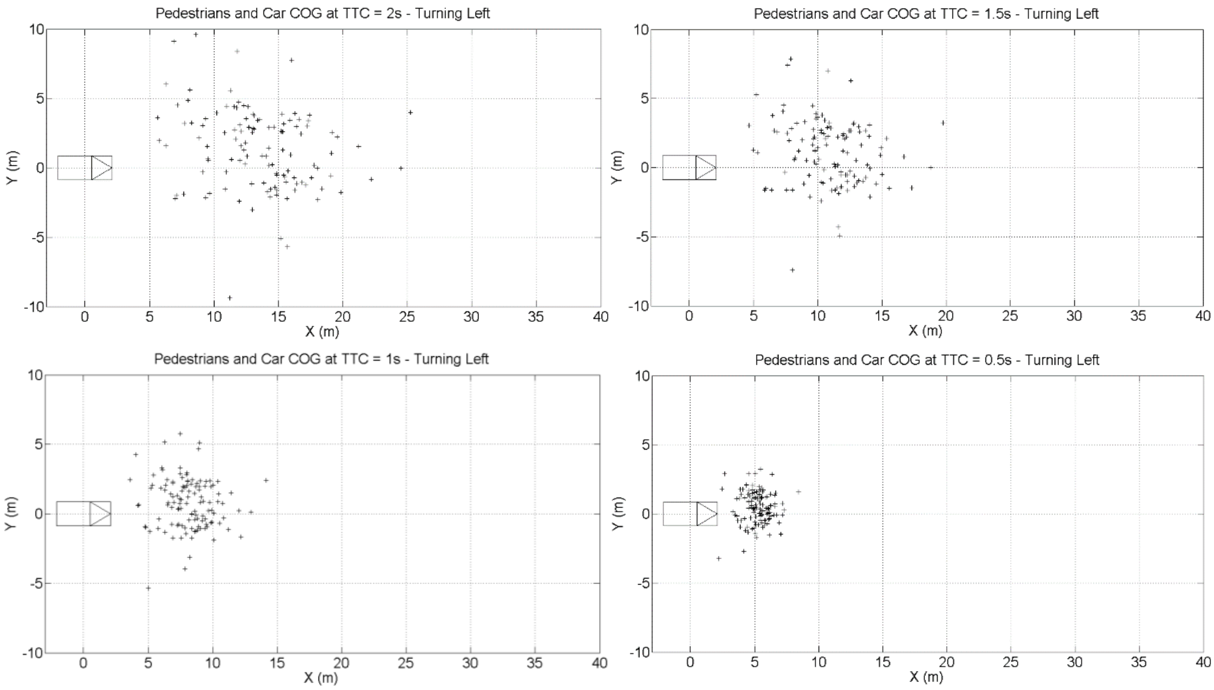


Figure 28: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-TL accidents (N = 124)

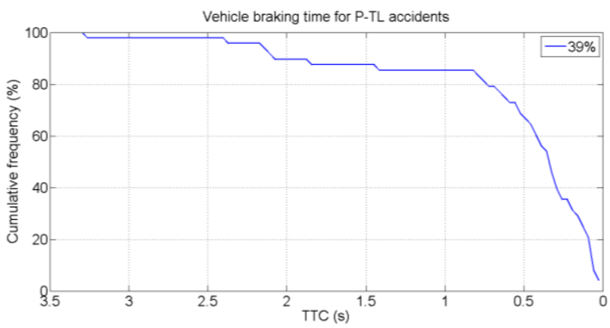


Figure 29: Drivers' braking timing for the P-TL scenario, 39% braking activation among 124 P-TL accident cases

Pedestrian Turning Right (P-TR)

Based on the classification section, 55 accidents among the 1509 are clustered into the TR scenario which represents 4% of our sample. Figure 30 gives the pedestrian relative positions to the car for P-TR scenarios. At TTC 2s prior the impact, pedestrians are located within 30m ahead the car's front, 15m at TTC 1s and 10m at TTC 0.5s. Similar to TL scenarios, the current representation does not reflect the turning manoeuver of the car. However, it can be noticed that in this scenario, more pedestrians are coming from the right side of the road. Those pedestrians who come from the right side, appears not to be in car's path even 0.5s prior the crash. On contrary, pedestrians coming from the left side, start to be in car's path 1s prior the collision and nearly all of them at TTC 0.5s.

From the brakes activation extraction, 13 drivers have initiated a braking manoeuver among the 55 P-TR cases, representing 24% brake activation for this scenario. Close to 80% drivers have triggered brakes 1s prior the impact and 50% less than 0.4s. Figure 31 shows the cumulative braking frequency of brake activation for this scenario.

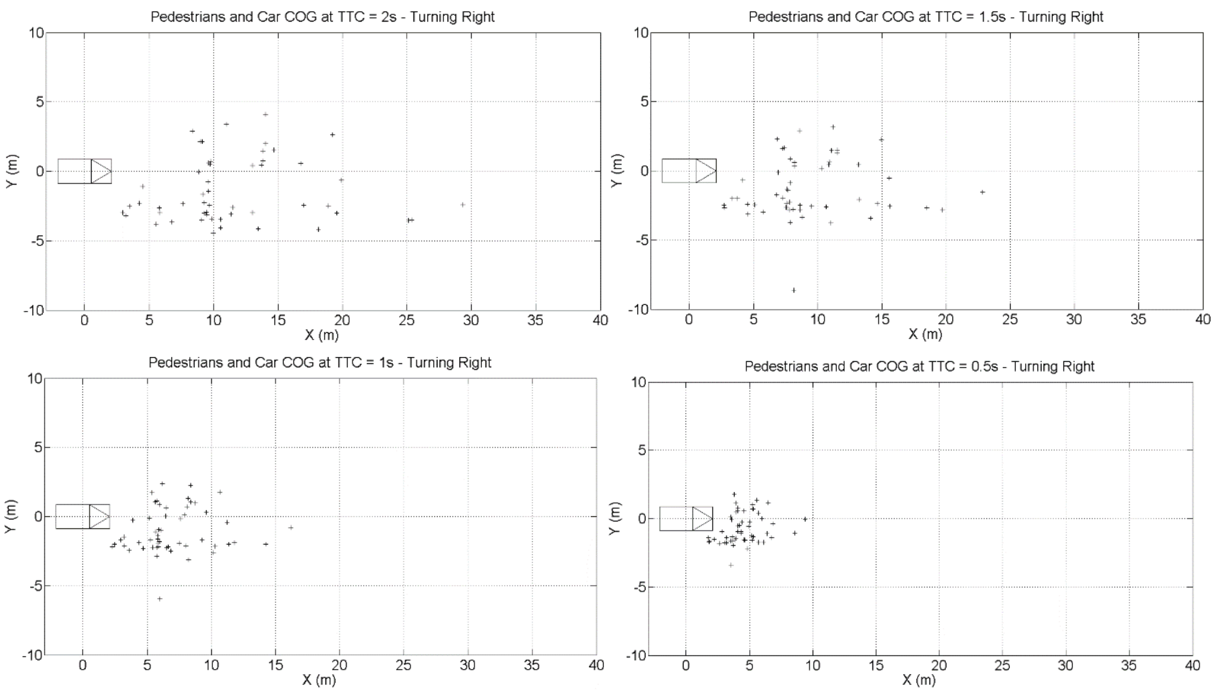


Figure 30: Pedestrians' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all P-TR accidents (N = 55)

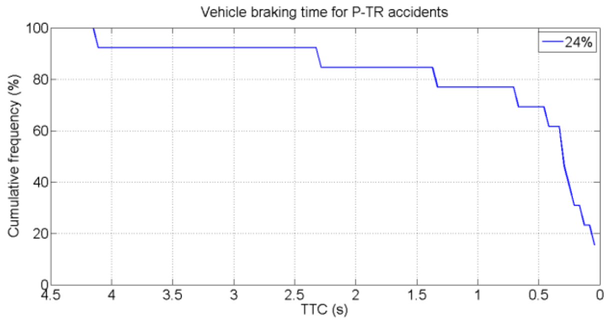


Figure 31: Drivers' braking timing for the P-TR scenario, 24% braking activation among 55 P-TR accident cases

2.4.1.2 Cyclist accident cases

Similarly to results for pedestrian, this section gives the results for cyclist accident cases. The sample is composed of 2261 accident cases involving one car and one cyclist. Results is given for the entire sample and then per scenario.

A visual representation of cyclist relative positions to the car for TTC 2s, 1.5s, 1s and 0.5s prior the impact is given in Figure 32. It shows that cyclists are scattered 2s before the impact but are within 40m ahead from the vehicle front and ±20m laterally to the car center line. At TTC 1s, the lateral distance has been reduced to ±10m as the distance ahead which is within 20m. At TTC 0.5s, nearly all cyclists are 10m ahead the car and within ±5m laterally. It can be noticed that only a few proportion of cyclists is in car's path 2s prior the collision and even 0.5s prior the impact. The proportion of cyclist within the ±3m laterally at TTC 1s and TTC 0.5s increases significantly between those two time intervals from 28% to 66%. This sudden rise may be explained by two elements alone or by the combination of them: displacement speeds and the trajectories of the car and the cyclist.

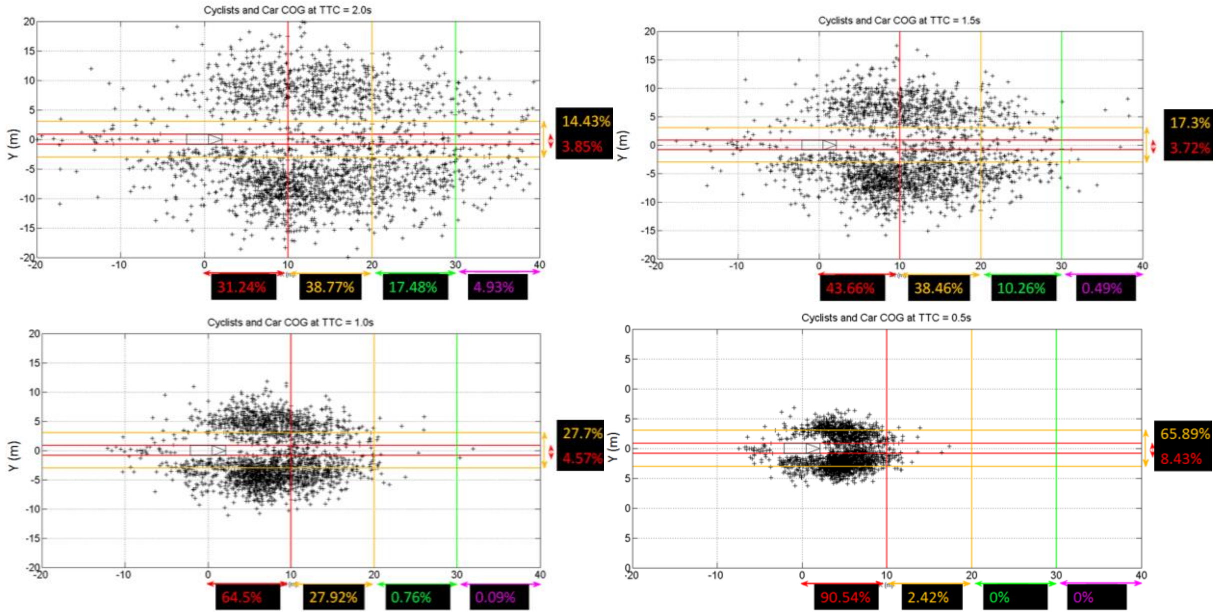


Figure 32: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all accident of our sample (N = 2261)

Drivers approach speed has been extracted. For recall, the approach speed corresponds to the travelling speed of the vehicle before the brakes activation. In the case brakes have not been activated, the approach speed is equal to the speed at the impact. Figure 33 right part gives the car travelling speed for our entire sample. It can be noticed that about 50% drivers were driving below 20km/h and 80% below 30km/h.

From the cyclist database, the proportion of brakes activation has also been extracted. Among all cases, only 33% of the drivers braked prior the collision. The brake trigger took place about 1s before the impact for 80% of the drivers. This proportion falls to 50% for activation 0.5s before the impact. Figure 33 left part shows the cumulative frequency of brakes activation.

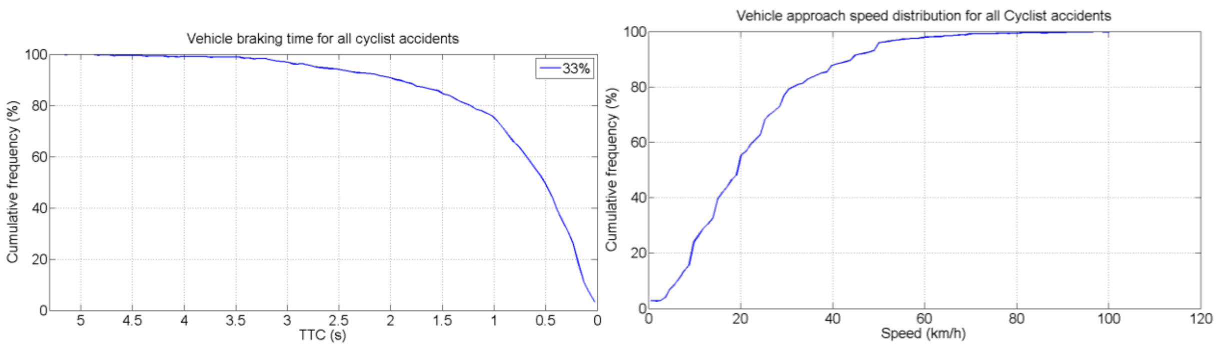


Figure 33: (Left) Cumulative frequency of brake activation timing (33% of all cases) and vehicle approach speed (Right), N = 2261

Based on the accident classification section, accident clustering reveals that our sample is composed in descending order of 33% CN scenario, 22% of CF scenario, 22% TR scenario, 12% TL scenario and 5% L scenario. The remaining 6% are clustered into the "Others" group as they do not enter into one of the five main identified scenarios. It can be noticed that half of our sample are crossing configurations and one third are turning situations.

Results per scenario for the relative position and the brake activation are given below. It provides information about scenario specificities.

Cyclist Crossing Nearside (C-CN)

Based on the accident classification section, 744 accident cases are clustered into the CN scenario which represents 33% of our sample. Figure 34 gives the cyclist relative positions to the car for C-CN scenario. From this figure, at TTC 2s prior the collision, cyclists are scattered up to 40m ahead the car's front and laterally ±20m. At TTC 1s, cyclists are still scattered 20m ahead and ±10m laterally and at TTC 0.5s cyclists are concentrated 10m ahead and ±5m laterally. It can be highlight that very few cyclists are in car's trajectory even 0.5s prior the impact. Another point that can be noticed concerns the provenance of the cyclist coming from the right side of the car. An explanation may come from the sample. In Germany and in France, cars drive on the right and as the definition of this scenario indicates that the cyclist is crossing from the closest side of the car, in these two countries, the closest side is the right one.

The brakes activation extraction reveals that 215 drivers have initiated a braking manoeuver among the 744 CN cases, representing 29% brake activation for this scenario. Close to 90% drivers initiated brakes 1s prior the collision. This rate falls to 60% when brakes are triggered at TTC 0.5s. Figure 35 shows the drivers' braking timing among those who have braked for this scenario.

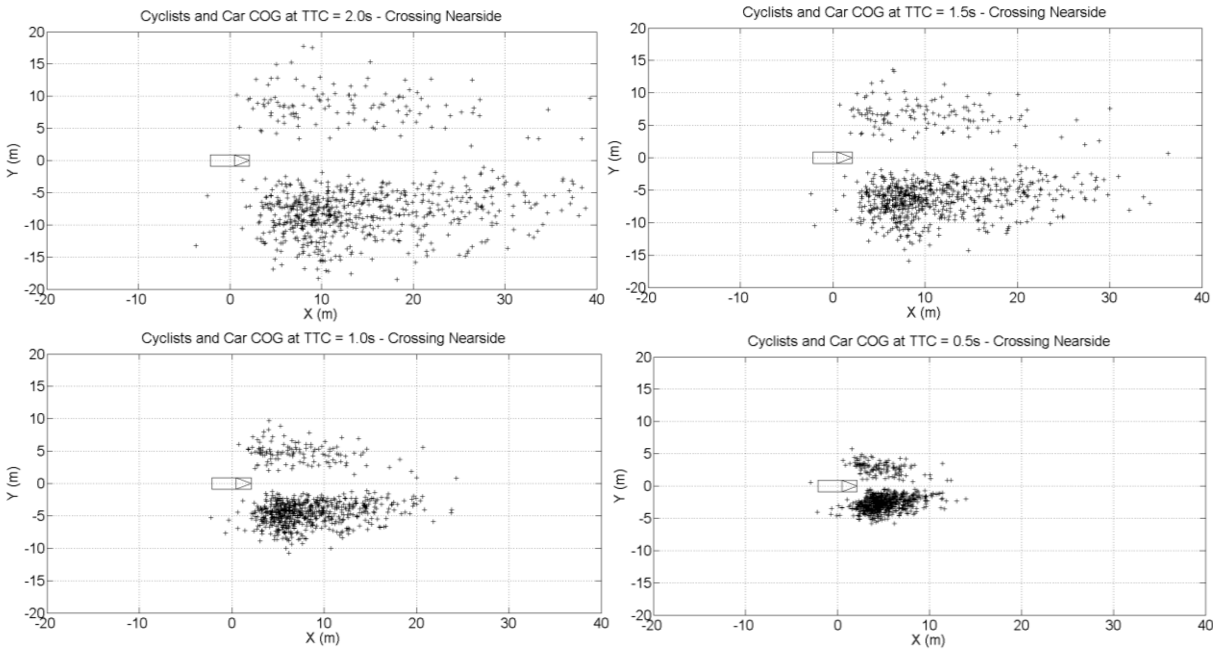


Figure 34: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-CN accidents (N = 744)

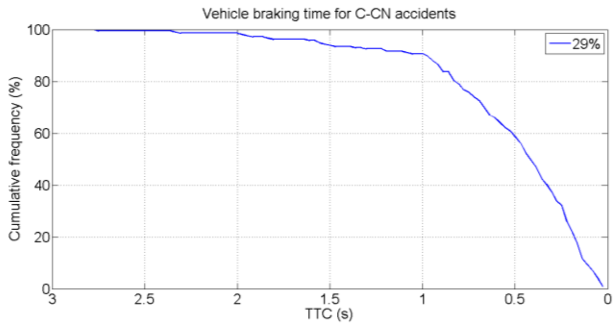


Figure 35: Drivers' braking timing for the C-CN scenario, 29% braking activation among 744 C-CN accident cases

Cyclist Crossing Farside (C-CF)

Based on accident classification section, 504 accident cases are clustered into the CF scenario which represents 22% of our sample. Figure 36 gives the cyclist relative positions to the car for C-CF scenario. From this figure, at TTC 2s prior the collision, cyclists are scattered 40m ahead car's front and ±20 laterally. At TTC 1s, cyclists are located up to 20m ahead and ±10m laterally and at TTC 0.5s, cyclists are concentrated 10m ahead the car and ±5m laterally. It can be observed that cyclists mostly come from the left side. It may be explained by the definition of the scenario and by the driving on the right rules in France and Germany. Also, it can be remarked that very few cyclists are on car's path even 0.5s prior the collision.

The brakes activation analysis reveals that 190 drivers have initiated a braking manoeuver among the 504 CF cases, representing 38% brake activation for this scenario. About 80% drivers have braked at TTC 1s and this rate falls to 50% when TTC is 0.5s. Figure 37 shows the drivers' braking timing among those who have braked for this scenario.

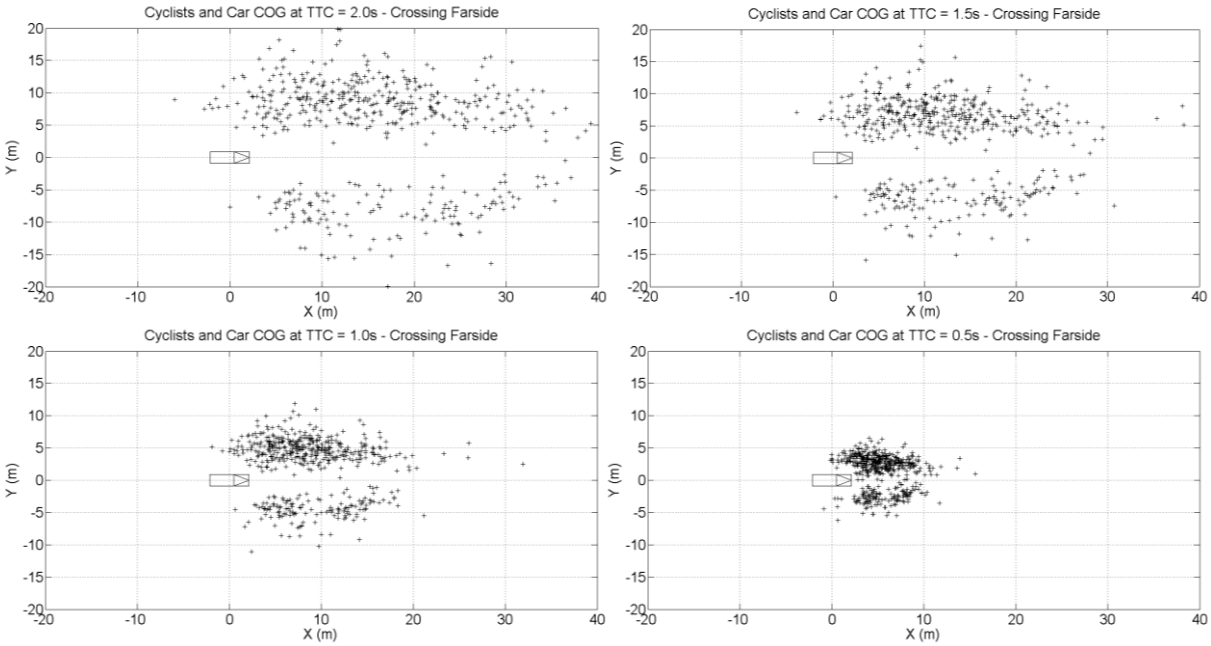


Figure 36: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-CF accidents (N = 504)

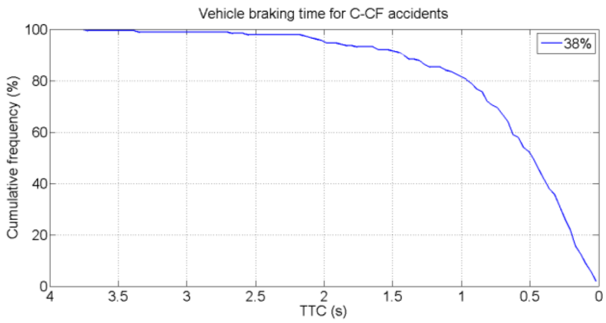


Figure 37: Drivers' braking timing for the C-CF scenario, 38% braking activation among 504 C-CF accident cases

Cyclist Longitudinal (C-L)

Based on accident classification section, 120 accident cases are clustered into the L scenario which represents 5% of our sample. Figure 38 shows cyclist relative positions to the car for C-L scenario. From this figure, from TTC 2s prior the impact to TTC 0.5s, most cyclists are in front of the car on the right side of the car. This can be explained by the scenario description that requires similar trajectories of the car and the cyclist. For the remaining cyclists not in front of the car, it may concern situations where the cyclists' speeds are higher and catch up the car. A collision may occur during a driving straight due to the trajectory deviation of the car and/or the cyclist.

The brakes activation analysis reveals that 40 drivers have initiated a braking manoeuver among the 120 L cases, representing 33% brake activation for this scenario. About 90% drivers have triggered brakes at TTC less than 2s. This proportion falls to 50% when brakes are triggered about 0.7s prior the collision. Figure 39 shows the drivers' braking timing among those who have braked for this scenario.

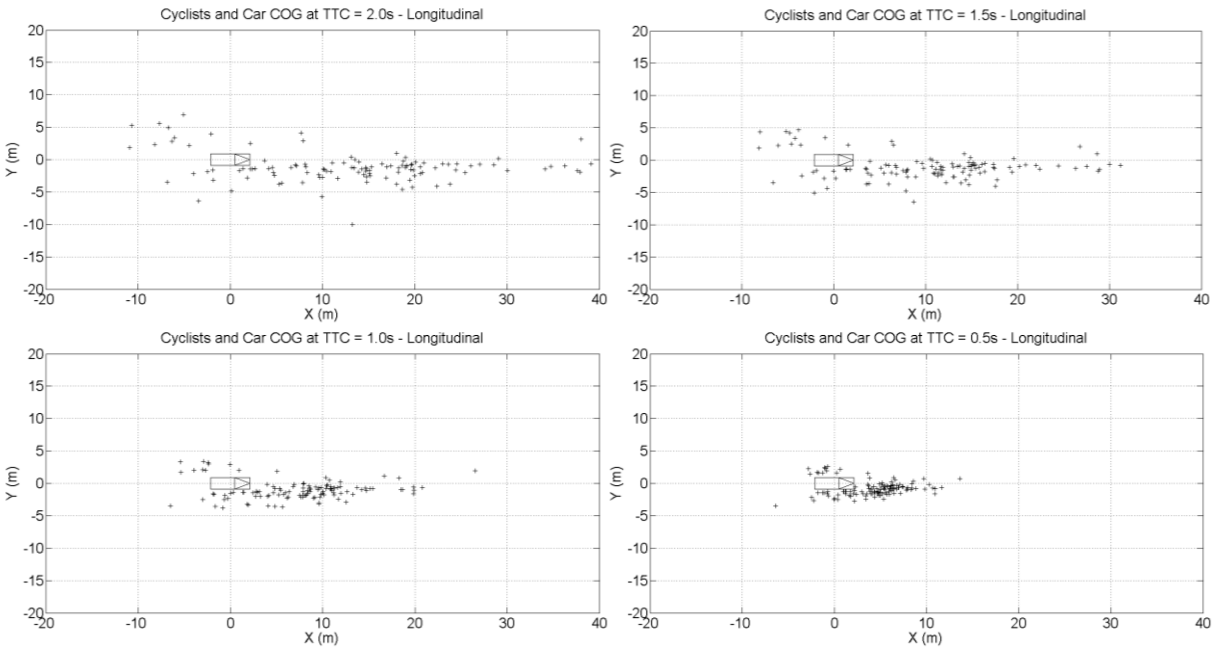


Figure 38: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-L accidents (N = 120)

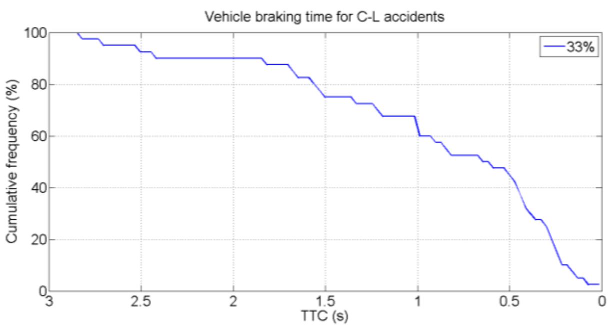


Figure 39: Drivers' braking timing for the C-L scenario, 33% braking activation among 120 C-L accident cases

Cyclist Turning Left (C-TL)

Based on accident classification section, 280 accident cases are clustered into the TL scenario which represents 12% of our sample. Figure 40 shows cyclist relative positions to the car for C-TL scenario. From this figure, cyclists are scattered at TTC 2s prior the collision until TTC 0.5s. At TTC 2s, cyclists are located 40m ahead and ±15m laterally. These values are reduced at TTC 1s to 20m ahead and ±10m laterally and to 10m ahead and ±5m laterally for TTC 0.5s. It can be noticed that more cyclists are coming from the right side of the car and that only a few of them are on car's path. The visual representation does not reflect the turning manoeuver of the car and also renders final combination of speed displacement of both the car and the cyclist.

The brakes activation analysis reveals that 97 drivers have initiated a braking manoeuver among the 280 TL cases, representing 35% brake activation for this scenario. About 80% drivers have braked at TTC less than 2s and this proportion falls to 50% when triggering happened at TTC 0.5s. Figure 41 shows the drivers' braking timing among those who have braked for this scenario.

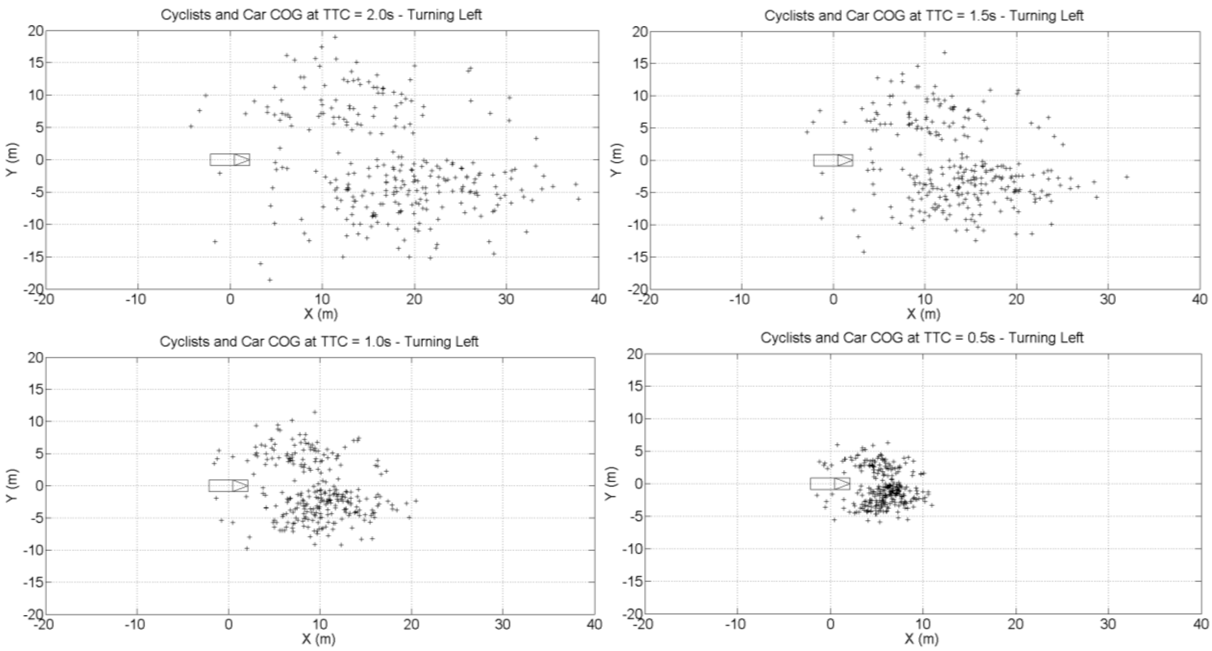


Figure 40: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-TL accidents (N = 280)

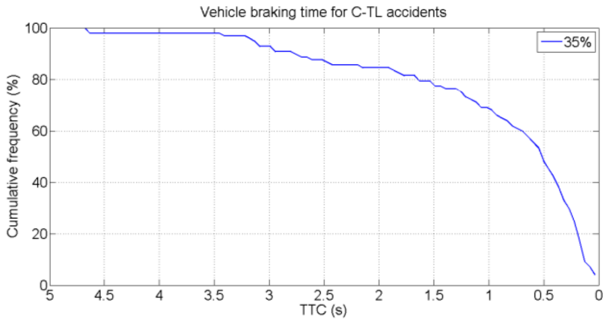


Figure 41: Drivers' braking timing for the C-TL scenario, 35% braking activation among 280 C-TL accident cases

Cyclist Turning Right (C-TR)

Based on accident classification section, 492 accident cases are clustered into the TR scenario which represents 22% of our sample. Figure 42 shows cyclist relative positions to the car for C-TR scenario. From this figure, cyclists are scattered at TTC 2s prior the collision within 40m ahead of the car and ±15m laterally. At TTC 1s, cyclists are located less than 15m ahead and less than ±10m laterally and at TTC 0.5s, cyclists are less than 10m ahead and within a ±5m laterally to car's center. It can be noticed that more cyclists are coming from the right side and also that very few cyclists are on car's path. However, readers have to keep in mind that this visual representation does not reflect the turning manoeuver of the car. It also reflects the final results of the speed displacement of both the car and the cyclist.

The brakes activation analysis reveals that 157 drivers have initiated a braking manoeuver among the 492 TR cases, representing 32% brake activation for this scenario. 80% drivers have braked at TTC 2s prior the impact and this proportion falls to 50% when triggering happened for TTC less than 1s. Figure 43 shows the drivers' braking timing among those who have braked for this scenario.

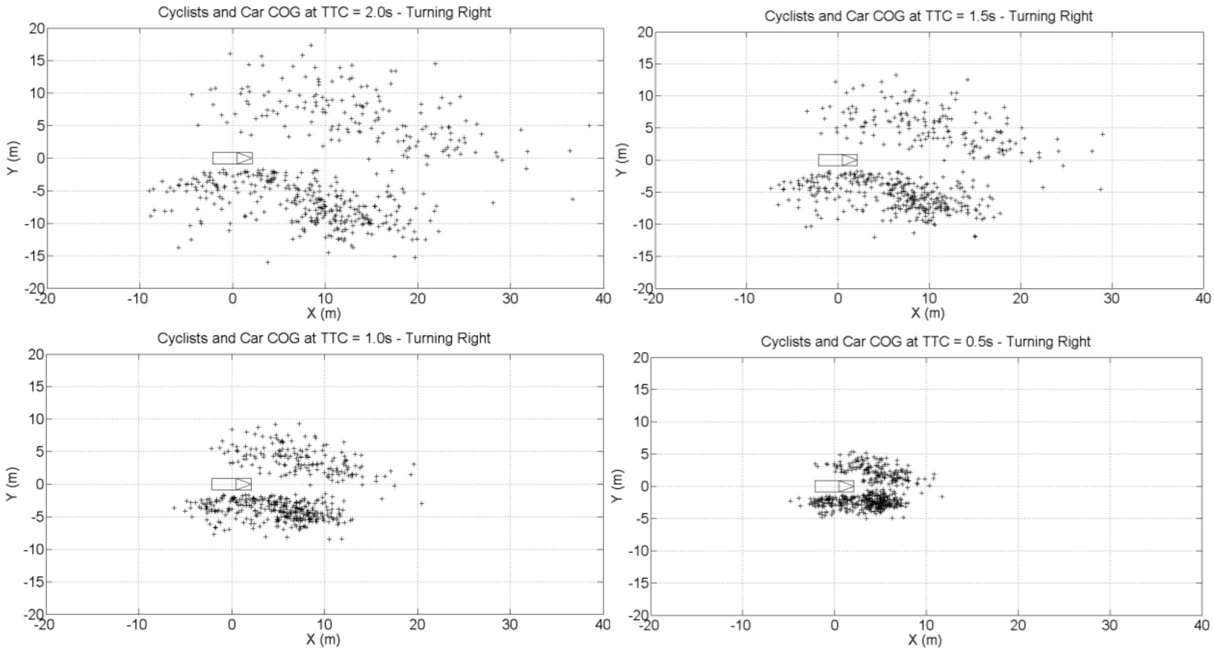


Figure 42: Cyclists' positions relative to the vehicle 2s, 1.5s, 1s and 0.5s before the impact for all C-TR accidents (N = 492)

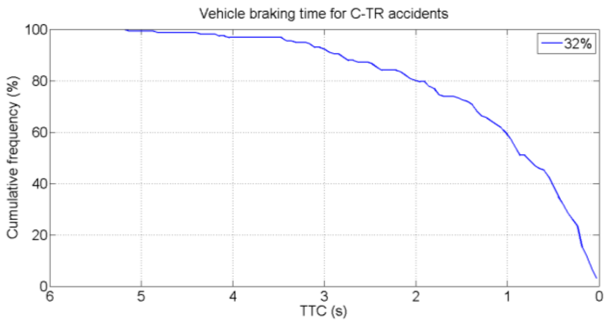


Figure 43: Drivers' braking timing for the C-TR scenario, 32% braking activation among 492 C-TR accident cases

2.4.1.3 Comparison between Pedestrian and Cyclist cases

Different comparison between pedestrian and cyclist cases will be presented in this section.

The comparison of all pedestrian cases versus all cyclist cases reveals that prior the collision, only a few percentage of pedestrian and cyclist can be located in car's direct path. It can be noticed that there are more pedestrians located within ±3m laterally to the car compared to cyclists. This difference might be explained by the displacement speed of the VRU. Pedestrian mean speed is about 5km/h (Huang et al. 2008) compared to cyclist which speed can goes up to 45km/h (Schleinitz et al. 2017). At TTC 2s, both pedestrians and cyclists can be found at a 40m far in front of the vehicle. Concerning car's approach speed, it can be remarked that most of the vehicle are travelling at 50km/h or below. Concerning the proportion of driver brake activation, more drivers have activated brakes when involved in a pedestrian accident compared to drivers involved in a collision with a cyclist. Nevertheless, the time where brakes are activated prior the collision is similar either for pedestrian or cyclist cases with a brake activation around 1s prior the impact. This difference in brake activation might be caused by driver awareness of the environment around him/her. Indeed, as cyclist speed is higher compared to pedestrian, it is more difficult to anticipate the cyclist's presence which can be less difficult to perceive in the surrounding environment. However, this is and remains a hypothesis that needs further investigation.

A comparison scenario per scenario will be presented here.

- For P-CN and C-CN: it can be remarked that more VRU are coming from the right of the car and only a few VRU can be located in front of car's direct path prior the collision. Drivers react less than 1s prior the impact in both cases with twice more reaction for drivers who collide a pedestrian compared to those who collide with a cyclist.
- P-CF and C-CF: for this type of scenario, more VRU are coming from the left side of the car. Drivers braking reaction results are similar to crossing nearside scenario with the same proportion difference.
- P-L and C-L: VRU are mainly located in front of the car and on the right side. Position on the right sight is logical for cyclists as they ride on the right side of the road and also for pedestrians if they walk on the road. Concerning brakes activation, more drivers react in cyclist cases compared to pedestrians. Pedestrian walking on the road might be a rarer event compared to cyclist riding on the road explaining the higher brake activation in cyclist cases. Thus this might also explain the earlier brakes activation in cyclist cases. It has to be highlight that the number of pedestrian sample is small and that conclusion and comparison might be biased by the small sample.
- P-TL and C-TL: A difference can be observed for VRU origin. For C-TL, it can be observed more cyclists coming from the right side compared to P-TL where the proportion is fairly spread. The higher proportion of cyclist coming from the right side has to be considered carefully as the cloud point figures correspond to the combination of car and cyclist displacement movement. Concerning the brake activation, the proportion are similar with a high majority of brake activation 1s prior the collision.
- P-TR and C-TR: For this scenario, it can be noticed that more VRU are coming from the right side of the car. Concerning the brake activation, it can be observed that a little more drivers trigger brakes in cyclist cases compared to pedestrians. A higher difference can be observed about brake activation time. In pedestrian cases, most drivers trigger brakes about 1s prior the impact whereas in cyclist cases, the activation proportion only reaches 60% 1s prior the impact. This activation rate reaches 80% when brakes are triggered 2s before the collision. The earlier brakes activation has to be considered carefully as it might be caused for different reasons. It might be a deceleration engaged by

the driver for the turning manoeuver without taking into consideration the cyclist or it might be an early emergency manoeuver. In the first case, it means that there is a lack in cyclist detection leading to the collision. In the second case, it might correspond to a moderate braking without enough intensity to avoid the collision. Further investigation is needed in order to distinguish those situations.

2.4.2 Field Of View (FOV)

This section gives the results of the detection rate during the progress of the accident for different FOV values. It has to be mentioned that the current analysis focus only on determining the FOV requirement without consideration of occlusion. The main interest of this section is to give an indication of detection performance depending on the choice for FOV values. This way, results are optimistic. The results are presented first for all accidents and then per scenario.

2.4.2.1 Pedestrian accident cases

The results for all pedestrian accident of our sample are given by Figure 44. It can be noticed that all detection curves increase to around 0.4s and then decrease to the collision except for FOV 10°. FOV 10° is the only curve that keeps decreasing to the impact. This may be explained by the accident progress. The closer to the impact, the more pedestrians can be detected as they were not previously detected. However, the decreasing curves less than 0.4s before the impact can be explained by the pedestrian leaving the detection cone and be at the vehicle side (outside the detection cone). It can also be noticed that detection rate for FOV higher than 30° allow detecting more than 90% pedestrian at TTC 2s prior the impact. However, starting from FOV 40° the gain with higher FOVs is strongly reduce because the detection rates are already close to the maximum.

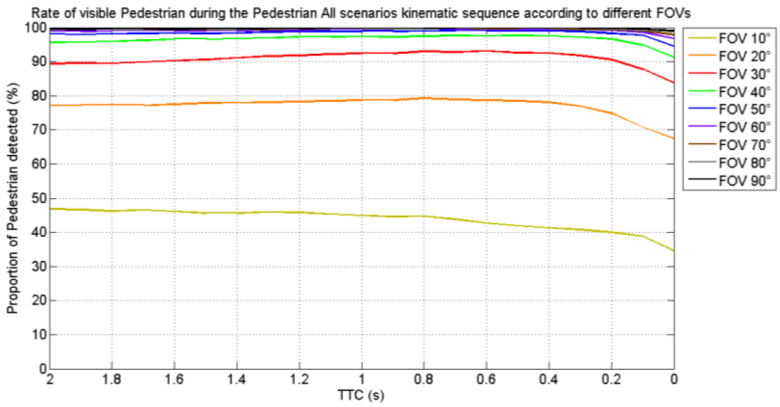


Figure 44: Rates of visible pedestrian for different FOV for all pedestrian accident cases, N = 1509

Pedestrian Crossing Nearside (P-CN)

Figure 45 illustrates the detection rate achieved for different FOV for P-CN scenario. It can be noticed that all curves have a tendency to decrease. The slope is higher when the TTC is very close to the impact (TTC lower than 0.2s). This trend can be explained by the fact that the detected pedestrian leaves the detection cone as he is not in front on the car but on its side when approaching the impact. This way, the slope is more important for lower FOV compared to higher FOV for whom the effect is reduced due to the more important detection field. An important gap exists between FOV 10° and other higher value. Indeed, the higher is the FOV, the more pedestrian should be detected which is confirmed here. It can also be noticed that the gain is very small from FOV starting to 40° as the gain for this FOV values are already close to 100%.

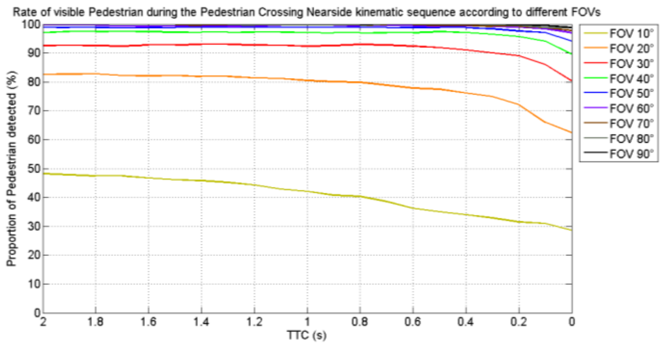


Figure 45: Rates of visible pedestrian for different FOV for P-CN accident cases, N = 788

Pedestrian Crossing Farside (P-CF)

Figure 46 illustrates the detection rate for different FOV for P-CF scenario. Detection rates appear to remain constant with fluctuations and decrease from a short moment prior the collision. Fluctuations can be explained by the alternation between inside and outside the detection cone during the kinematic progress. However at the very end when coming closer to the impact, the detection rates fall. The explanation is the same as for the crossing nearside. The pedestrian is not in front of the car but on its side and outside the sensors field. It can be remarked that for FOV higher than 40°, the gain is small as the detection rates are already close to 100%.

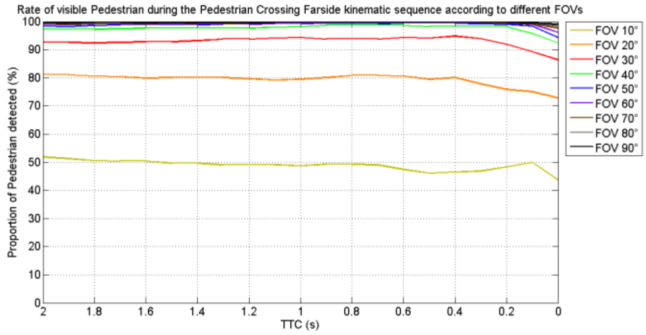


Figure 46: Rates of visible pedestrian for different FOV for P-CF accident cases, N = 461

Pedestrian Longitudinal (P-L)

Figure 47 illustrates the detection rate for different FOV for P-L scenario. Detection rates are similar for all FOV values except for FOV 10 and 20°. For FOV 10 and 20°, the detection rates decrease for TTC lower than 0.8s. This trend can be explained by the configuration of the scenario. Indeed, a pedestrian and a car are going in the same direction and a collision between those two participants happened. A pedestrian may potentially walk on the road but will stay on one side of the road and not on the center. That is why, when getting closer to the impact location, pedestrians leave the detection cone. For FOV values higher than 30°, detection rates are and remain at maximum value of 100%. The configuration of this scenario can explained this high detection rate. In fact, this is the only scenario in which the FOV value is less important.

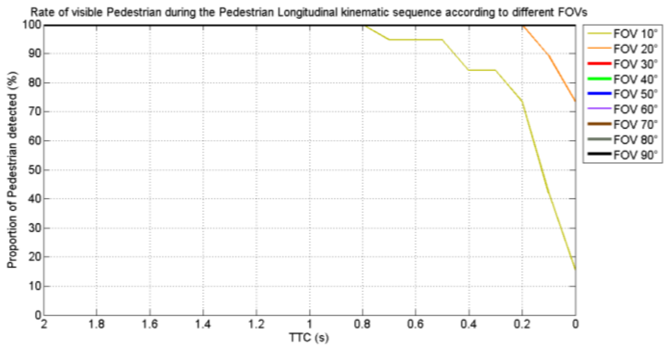


Figure 47: Rates of visible pedestrian for different FOV for P-L accident cases, N = 20

Pedestrian Turning Left (P-TL)

Figure 48 illustrates the detection rate for P-TL scenario. Detection rates increase and decrease at a TTC close to the impact. This trend can be observed for all curve values revealing that pedestrians keep entering the detection FOV when approaching the impact time. Close to the impact time, some pedestrians leave the detection cone similarly to crossing scenarios previously described. It can be noticed that for FOV lower than 40°, the detection gain at TTC 2s until the detection peak can be important up to 40% for FOV 10°. The gain begins to be smaller starting from FOV 40° to higher value. Even if detection rates are optimistic due to the no consideration of occlusion, it has to be highlighted that those values can be sensitive to the accident configuration. Indeed, depending on the accident circumstances, i.e. the infrastructure, the collision location, the moment of the impact which can be at the beginning of the turning manoeuver, in the middle or in the end, drivers' turning style and etc. detection values can then be affected. Thus, values have to be considered carefully due to sample possible bias. This remark is also valid for the turning right analysis.

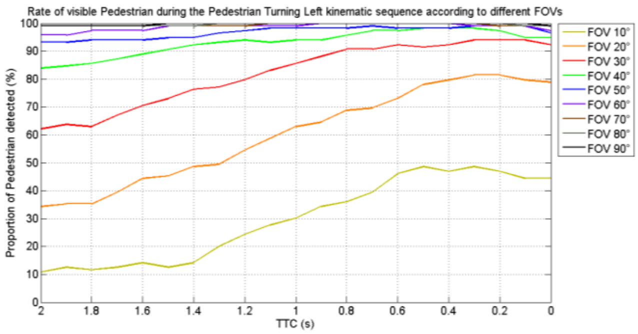


Figure 48: Rates of visible pedestrian for different FOV for P-TL accident cases, N = 124

Pedestrian Turning Right (P-TR)

Figure 49 illustrates the detection rate for P-TR scenario. Detection rates are similar to previous observed scenario trend except for Longitudinal with an increase and a decrease. However in this case, it can be observed that fluctuations are more important compared to the other scenarios. This can be explained by the position of the pedestrian during the turning manoeuver. 2s prior the collision, the vehicle is turning. It may be at the beginning, in the middle or at the end of the manoeuver. From previously pedestrian position relative to the car, it can be observed that pedestrians can come from the right or the left. This way, if the car is turning, some pedestrians on the right side can enter the detection cone whereas the pedestrians on the left leave it. This alternation of new detected and those who disappear from the detection cone explains that phenomenon. Similarly to other scenarios, the detection gain is important for FOV lower than 40°. Starting from 40°, the gain becomes smaller and smaller as nearly all pedestrians are detected.

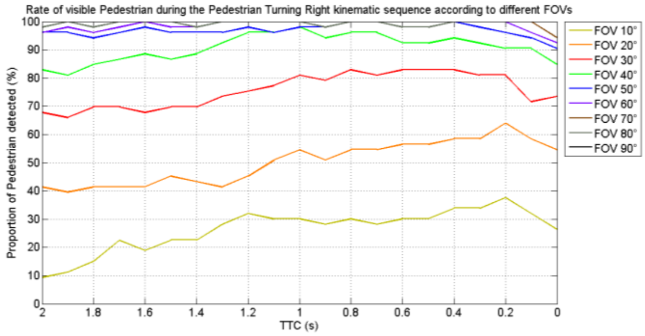


Figure 49: Rates of visible pedestrian for different FOV for P-TR accident cases, N = 55

2.4.2.2 Cyclist accident cases

This section presents the results for all cyclist accident cases of our sample at first, and then results per scenario are given.

Figure 50 presents cyclist detection rate during the accident kinematic according to different FOV values from TTC 2s to the impact. It can be noticed three different curve evolutions. Detection rates for FOV 10 and 20° decrease and then increase about 0.5s prior the impact, detection rate for FOV 30 and 40° keep increasing and finally detection rate increase and decrease starting from TTC 0.5s. The curves decrease from TTC 2s to TTC 0.5s can be explained by the very small detection cone for FOV 10 and 20°. Indeed, as the detection cone is very small, the proportion of cyclists that can be detected correspond only to cyclist that are located in front of the car at a certain distance to the car. Due to the lateral position of cyclists who ride on the road on the right side, the smaller is the distance between the car and the cyclist the more cyclists leave the detection cone. Thus, the lateral position of cyclist and the small detection cone are responsible of this detection reduction when approaching the collision time. On contrary for higher FOV values (more than 30°), cyclists keep entering the detection cone showing that 30° may be sufficient not to have a reduction detection. From TTC 0.5s to the impact, two trends can be observed, a detection increase on the one hand and on the other hand a detection decrease. The detection increase can be explained by cyclists entering the detection cone and by the proximity with the impact in time. The decrease can be explained due to the large detection cone and to cyclist lateral position. The large detection cone allows detecting most cyclists in front and on the side of the car. However, some cyclists initially detected leave the detection cone as they are located too laterally to the car's path. As a collision still occurs, it corresponds to impact on the side of the car.

It can be remarked that a FOV 40° allows detecting more than 50% cyclists at least 2s prior the impact. The gain for higher FOV is strongly reduced between FOV 60 and 70°. It reveals that increasing the FOV will result in a small detection improvement. Additionally, it can be observed that a non-neglected proportion of cyclists cannot be detected prior the collision. It corresponds to cases where the cyclists may come from behind the car or to situation where the cyclist impacts the car on its side.

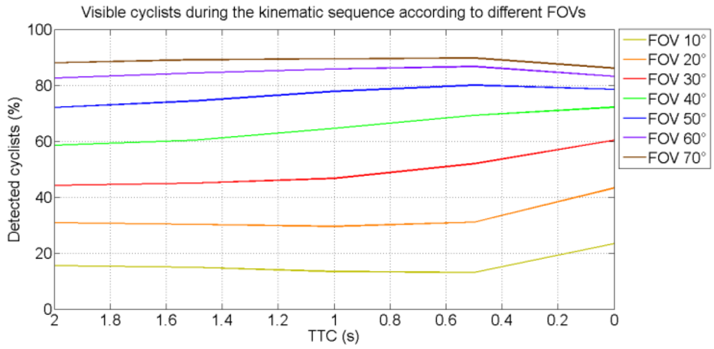


Figure 50: Rates of visible cyclists for different FOV for all Cyclist accident cases, N = 2261

Cyclist Crossing Nearside (C-CN)

Figure 51 illustrates the detection rates for C-CN scenario. Detection rates have a similar evolution as curves for all accident cases. FOV detection values go from 10 to 90%. Low FOV values (10 to 40°) have a detection progression up to 20% at the impact compared to TTC 2s. For FOV 50° and higher, a detection gain can still be observed with a decrease approaching to the impact. It can be remarked that more than 90% cyclists can be detected with a 70° FOV and a FOV 40° is sufficient to detect more than 50% cyclists.

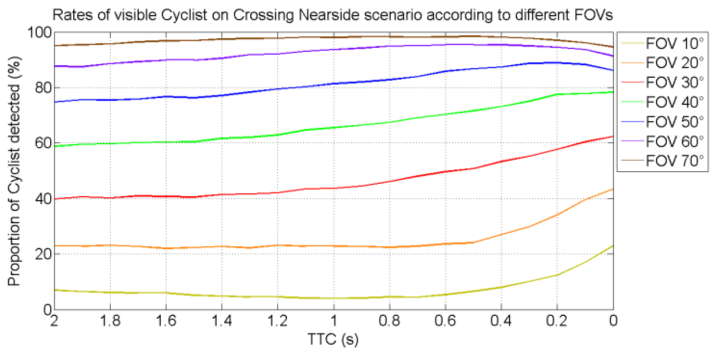


Figure 51: Rates of visible cyclists for different FOV for C-CN accident cases, N = 744

Cyclist Crossing Farside (C-CF)

Figure 52 illustrates the detection rates for C-CF scenario. Results are similar to C-CN scenario. The detection rate for the highest studied value allows detecting more than 90% cyclists of all C-CF cases. However, contrary to C-CN scenario, a FOV of only 30° allows detecting about 50% cyclists 2s prior to the collision.

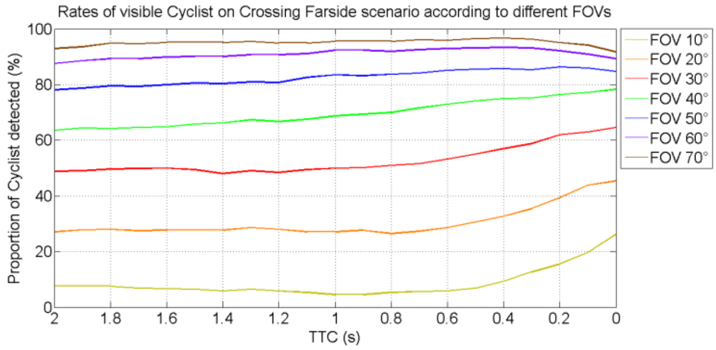


Figure 52: Rates of visible cyclists for different FOV for C-CF accident cases, N = 504

Cyclist Longitudinal (C-L)

Figure 53 illustrates the detection rates for C-L scenario. Results reveal that all detection rates tend to decrease coming closer to the impact. This trend can be explained by the configuration of this scenario. Indeed, in this configuration the cyclist and the car go in the same direction. However the car is positioned in the center of the way contrary to the cyclist who rides on the right side of the way. This lateral position on the road is responsible of the decreasing detection rate. When the car is far from the vehicle, the cyclist is inside the detection cone. When approaching the impact location, due to its lateral position the cyclist leaves the detection cone. This phenomenon is more important for low FOV values. Detection rates have the highest value at TTC 2s for all FOVs and it can be expect to have higher value for TTC earlier to 2s. It can be noticed that in this particular scenario, detection rates reached more than 50% even for the smallest FOV analyzed in this study, revealing that FOV parameter value has less importance in this scenario compared to other scenarios.

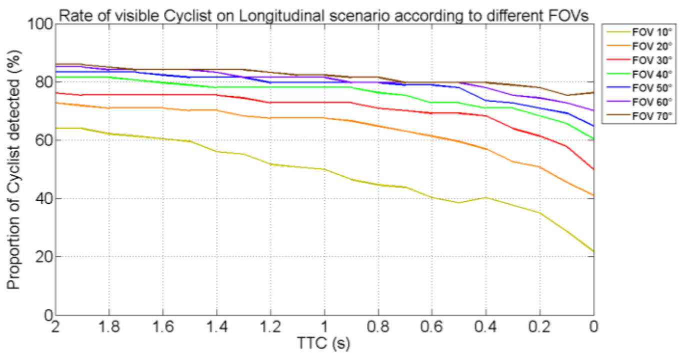


Figure 53: Rates of visible cyclists for different FOV for C-L accident cases, N = 120

Cyclist Turning Right (C-TL)

Figure 54 illustrates the detection rate for C-TL scenario. Results show that detection curves remains stable and decrease close to the impact for FOV 20° and lower. For higher FOV values, detection rates increase and decrease. It can be noticed a detection rate higher than 90% for the highest FOV considered in this analysis at TTC 2s.

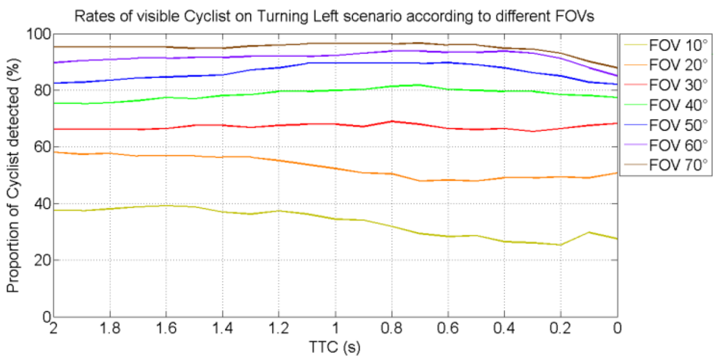


Figure 54: Rates of visible cyclists for different FOV for C-TL accident cases, N = 279

Cyclist Turning Right (C-TR)

Figure 55 illustrates the detection rate for C-TR scenario. Detection curves increase for FOV 50° and lower whereas higher FOV detection rates remain stable. Even with the highest detection rate of 70° in this study, only 80% cyclists are detected.

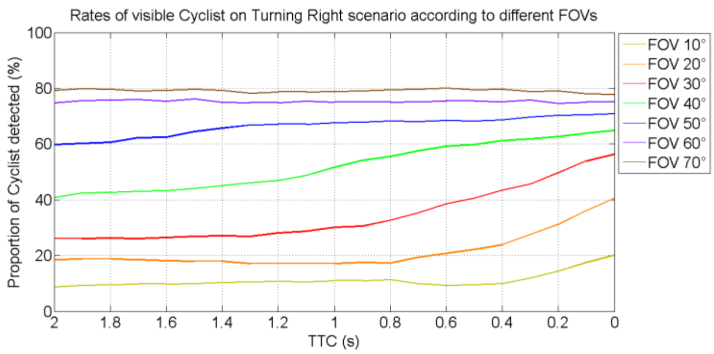


Figure 55: Rates of visible cyclists for different FOV for T-CR accident cases, N = 492

2.4.2.3 Comparison between Pedestrian and Cyclist cases

This section compares FOV detection results between all pedestrians and cyclists and per scenario.

Differences in detection rates can be observed when considering all cases. First, detection curve trends are different. For pedestrian cases, detection rates only decrease while on contrary for cyclist cases, detection rate can increase and then decrease. The increase in cyclist detection can be explained by cyclist displacement speed. Due to its higher displacement speed, cyclist can be located farther to the car, requiring a higher detection cone. The closer the kinematic progresses to the impact, the closer are cyclists to the car and the more of them can be detected. However, at a certain time prior the impact (at TTC about 0.5s), detection rates decrease for high FOV values (50° and higher). This trend can be explained by the cyclist position during the kinematic. It corresponds to cases where the cyclist collides the car on its side and not in the front. Depending on the travelling speed of both the car and the cyclist, it may be possible that it is not the car that impacts the cyclist but the opposite. This explains the cyclist decreasing detection rate. For pedestrians, the detection rate decreasing can be explained in a similar way. This effect is more visible for lower FOV value with a higher decline.

Second, the detection rate values are different. Indeed, at TTC 2s prior the impact, the detection rates start up to 45% and can reach 100% for pedestrian cases compared to the 15% to 90% for cyclists. It reveals that there is a non-neglected proportion of cyclist cases where the cyclist cannot be detected with the highest considered FOV value of 70° in this study. This proportion of cases still exist for pedestrian cases but is much smaller compared to cyclist ones. The shift difference in detection rate can be caused by the displacement speed. Prior the collision, pedestrians are closer to the car's path and thus require a lower FOV to be detected. These results are confirmed by Lenard et al. (2018). In their analysis on an English database, they suggested a ±20° FOV for 80% pedestrian detection and ±80° for 90% cyclist detection. Similar results can be found in our analysis. Close to 80% pedestrian can be detected at TTC 2s prior the impact with a FOV 20° whereas a 70° FOV allows detecting about 90% cyclists. To detect most pedestrians, a FOV 40° may be enough to cover a very important part of pedestrian accidents. This result matches Hamdane et al. (2015) study where they estimated that a 35° FOV can be sufficient to affect most crashes. This reveals one major difference in VRU detection. A low FOV is required for pedestrians whereas a high FOV is required for cyclists. An additional remark for cyclist is that a FOV 40° is required to be able to detect at least 50% cyclists.

A comparison scenario per scenario is given below.

- P-CN and C-CN: Results are similar to those described for all accident cases. For pedestrian cases, FOV values higher than 40° give only a small additional gain. For cyclist cases, a gain can be observed between FOV with a smaller gain between FOV 60 and 70°. Additionally, it can be observed that 70° FOV nearly allows detecting all cyclists for this configuration. For a 40° FOV, more than 50% cyclists can be detected.

- P-CF and C-CF: Results are similar to crossing nearside scenario. 40° and 70° is sufficient to be able to detect most pedestrians and cyclists for this scenario. The FOV 40° value is required to detect at least 50% cyclists.

- P-L and C-L: A common trend can be observed for this scenario. In a general way, detection curves decrease the closer to the impact. This trend can be explained by the configuration of the scenario and VRU position. The closer to the impact the higher FOV is required to still detect the VRU located on the right side of the car. This is why, the higher

FOV value have a lower decline compared to small FOV. It can be remarked that for pedestrian cases, a 10° FOV is enough to detect all pedestrians 2s prior the impact. This is due to the scenario configuration. For cyclist cases, it can be remark that in some cases cyclists can never be detected. Those cases correspond to accidents where the cyclist is initially located behind the car. As they travel at speed higher than car's one, the impact occurs on the side of the car as impact on the car rear impact have been exclude from this scenario and from analysis. These cases can represent up to 20%. Despite those undetected cyclists, more than 80% cyclists can be detected.

- P-TL and C-TL: Trends are different between pedestrian and cyclist cases. For cyclist cases, detection curves tend to be stable and decline close to the impact whereas for pedestrian detection curves generally increase and slightly decline close to the impact. Detection rates go from 10 to close to 100% for pedestrian cases and from 40% to more than 90% for cyclists. Results reveal that high FOV is required to detect more VRU. However, in order to have at least 50% VRU detection, a 30° FOV is required at TTC 2s prior the collision.

- P-TR and C-TR: Curves reveal similar detection evolution except for pedestrian cases close to the impact. For low FOV values, the detection rates increase whereas higher FOV detection rates remain stable. Only for pedestrian cases, there is a decline in detection rates very close to the impact. This decline is caused by the pedestrian leaving the detection cone due to the vehicle turning manoeuver. A difference can be observed for detection rates. In pedestrian cases, the maximum detection rate is close to 100% contrary to cyclists where maximum rate is limited to 80%. It shows that in about 20% cases, a FOV 70° is not sufficient to detect cyclists in this configuration. To reach at least 50% detection rate for both VRU, a FOV 50° is required.

2.4.3 Range

This section presents results concerning the detection rate in a general cases for pedestrian and cyclist cases. Then results per scenario will be presented to highlight scenario specificity.

2.4.3.1 Pedestrian accident cases

Results are presented first considering all cases from our sample, then results per scenario.

Different range values have been analyzed based on the cloud point figures up to 45m. Figure 56 presents detection rates for all pedestrian cases. Global results for pedestrian cases show that 45m detection range is sufficient to nearly detect all pedestrians at TTC 2s prior the impact. To detect at least 50% pedestrians a TTC 2s, a 25m range is required.

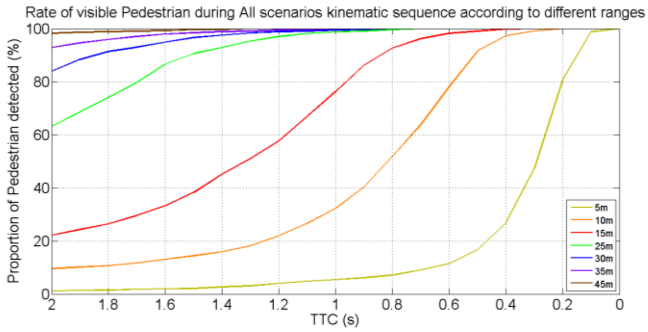


Figure 56: Range detection rates for all pedestrian cases, N = 1509

Pedestrian Crossing Nearside (P-CN)

Figure 57 illustrates detection range for pedestrian crossing nearside scenario. Results show that nearly all pedestrians are in a radius of 45m around the car 2s prior the impact. However, the gain between a range of 35m and 45m is small at a TTC 2s prior the impact.

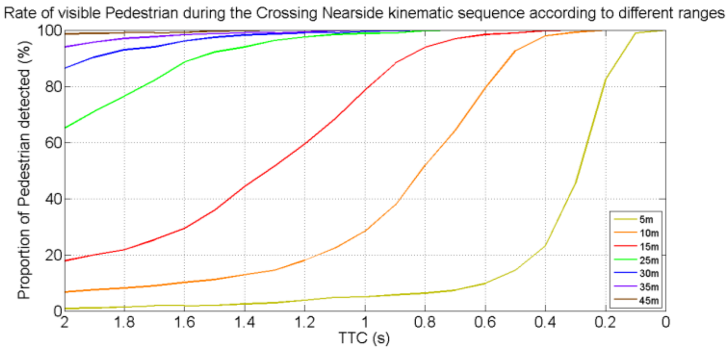


Figure 57: Range detection rates for pedestrian crossing nearside scenario, N = 788

Pedestrian Crossing Farside (P-CF)

Figure 58 illustrates detection range for pedestrian crossing farside scenario. Results are similar to the crossing nearside scenario. A 45m range allows detecting nearly all pedestrians and the gain between 35m and 45m is small at TTC 2s.

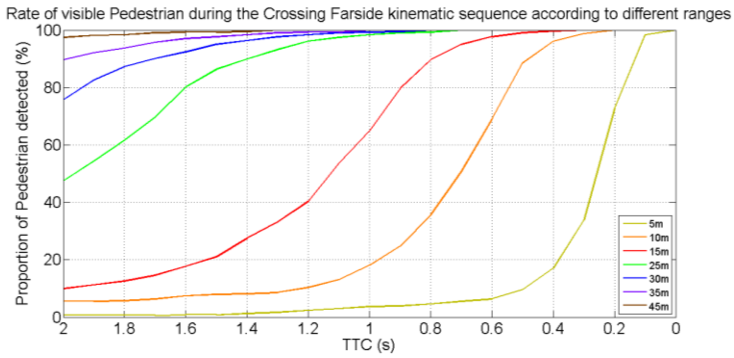


Figure 58: Range detection rates for pedestrian crossing farside scenario, N = 461

Pedestrian Longitudinal (P-L)

Figure 59 illustrates detection range for pedestrian longitudinal scenario. Results show that a 45m range allows detecting about 90% pedestrians 2s prior the collision. This rate falls to 80% for a 35m range.

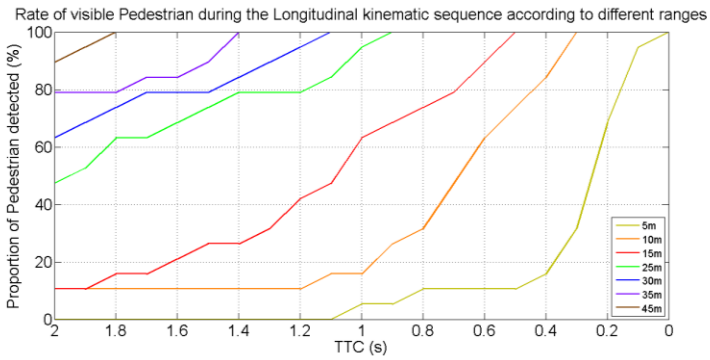


Figure 59: Range detection rates for pedestrian longitudinal scenario, N = 20

Pedestrian Turning Left (P-TL)

Figure 60 shows results for the pedestrian turning left scenario. A 25m range appears to be sufficient to detect all pedestrians at TTC 2s prior the impact.

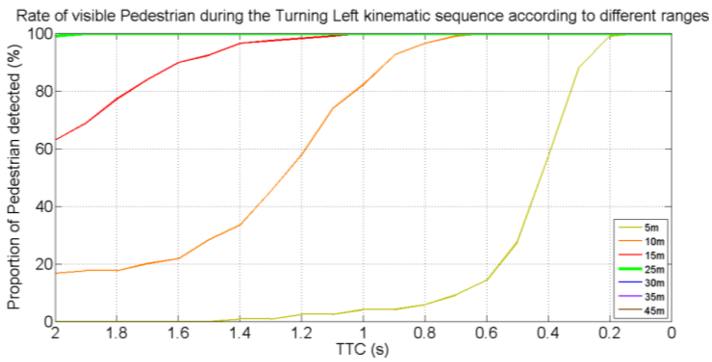


Figure 60: Range detection rates for pedestrian turning left scenario, N = 124

Pedestrian Turning Right (P-TR)

Figure 61 shows range detection rates for pedestrian turning right scenario. Results show that more than 90% pedestrians are detected 2s prior the impact with a 25m range and a 30m range is sufficient to have a 100% detection rate.

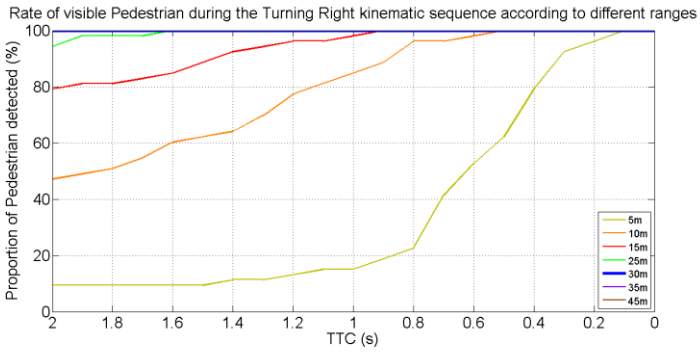


Figure 61: Range detection rates for pedestrian turning right scenario, N = 55

2.4.3.2 Cyclist accident cases

Results are presented for all cyclist cases at first and then per scenario.

Figure 62 shows the results for all cyclist accident cases. A 45m range appears to be sufficient to detect nearly all cyclists at TTC 2s. The gain starting from range 30m is highly reduced at TTC 2s.

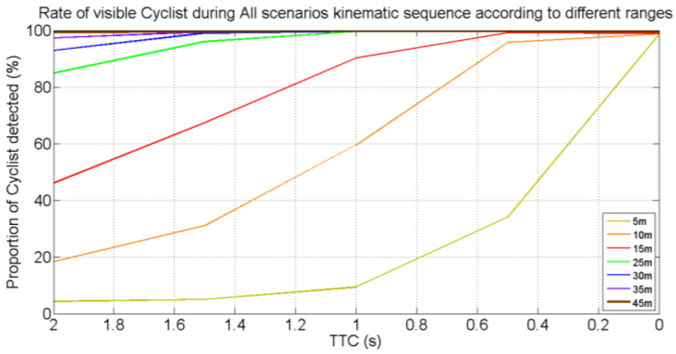


Figure 62: Range detection rates for all cyclist cases, N = 2261

Cyclist Crossing Nearside (C-CN)

Figure 63 shows the detection rates for cyclist crossing nearside scenario. It reveals that a 45m is sufficient to detect all cyclists at TTC 2s prior the impact. However, it can be noticed that the gain between a 35m range and 45m is small.

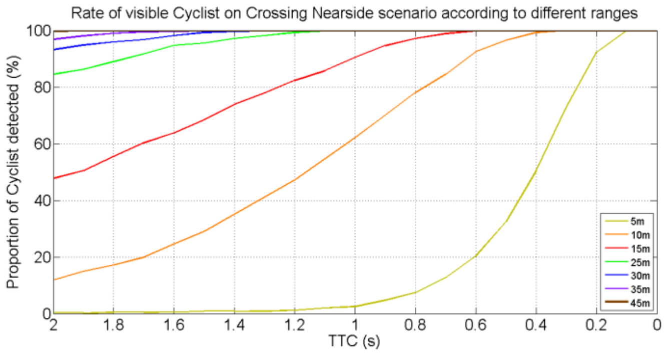


Figure 63: Range detection rates for cyclist crossing nearside scenario, N = 744

Cyclist Crossing Farside (C-CF)

Figure 64 shows the range detection rate for cyclist crossing farside scenario. It shows that 45m is sufficient to nearly detect all cyclists at TTC 2s prior the impact. The gain at TTC 2s between a 35m range and 45m is small.

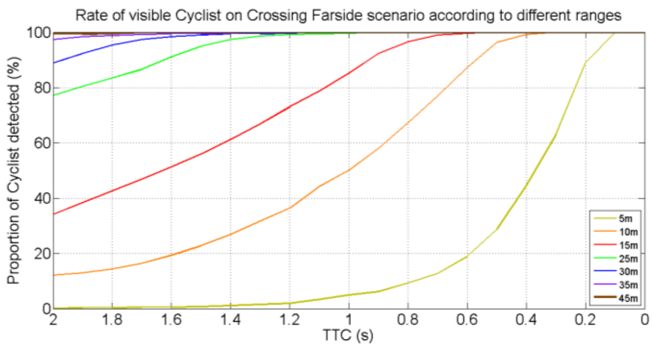


Figure 64: Range detection rates for cyclist crossing farside scenario, N = 504

Cyclist Longitudinal (C-L)

Figure 65 shows the range detection rates for cyclist longitudinal scenario. A 45m range is sufficient to detect all cyclists at TTC 2s prior the impact. At TTC 2s, a 35m range still allows the detection of 90% cyclists.

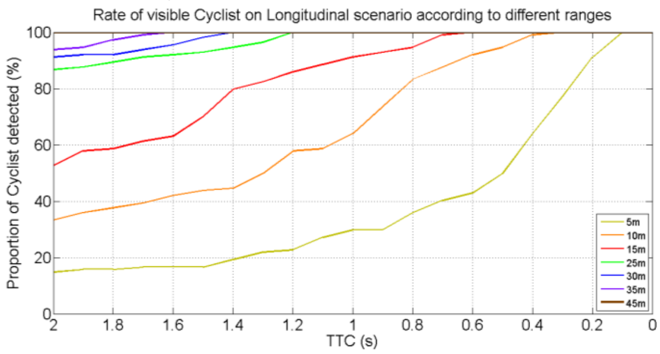


Figure 65: Range detection rates for cyclist longitudinal scenario, N = 120

Cyclist Turning Left (C-TL)

Figure 66 shows the range detection rates for cyclist turning left scenario. It reveals that 45m is sufficient to detect all cyclists at TTC 2s. It can be noticed that the gain between 35m and 45m at TTC 2s is small.

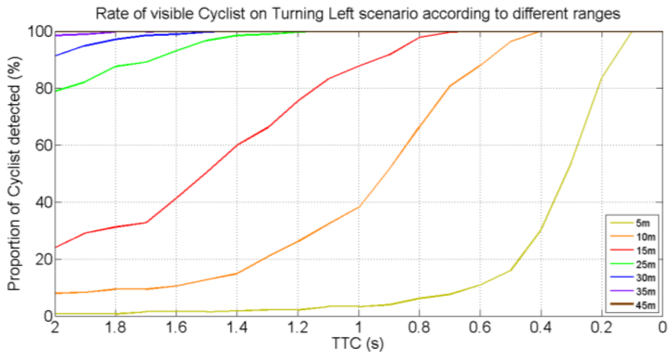


Figure 66: Range detection rates for cyclist turning left scenario, N = 280

Cyclist Turning Right (C-TR)

Figure 67 shows the range detection rates for turning right scenario. A 45m range is sufficient to detect all cyclists at TTC 2s. The gain is small between 35m and 45m at TTC 2s.

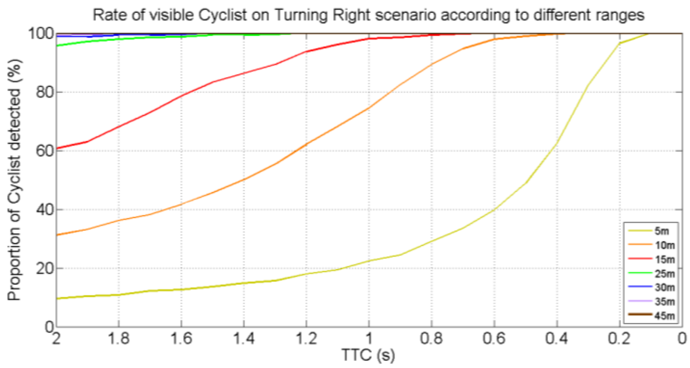


Figure 67: Range detection rates for cyclist turning right scenario, N = 492

2.4.3.3 Comparison between Pedestrian and Cyclist cases

This section makes a comparison between all pedestrian and cyclist cases at first. Then a comparison per scenario is given.

In a general case, for low range value, more cyclists are detected compared to pedestrians. When range value is higher than 30m, detection rates start to be similar. This difference in detection range for low values can be explained by car displacement speed seen in section 2.4.1.1 and 2.4.1.2.

On our sample, a 45m range allows the detection of nearly all pedestrians and cyclists at TTC 2s. However, it can be noticed that the gain between range 35m and 45m is small at TTC 2s. In order to reach at least 50% detection, a minimum 25m range is required. The small proportion cases where the VRU is outside the detection range correspond to accident cases where car's travel speed is high. A high proportion of VRU can be detected with a 25m range at TTC 2s. This value corresponds to car travel speed below 50km/h which is urban travel speed limit. As the gain is reduced from 25m range, it shows that car's sensors should at least have this value 2s prior the collision. 25m is a range that can be easily reached by sensors as presented by Muktar et al. (2015).

Comparison per scenario is given next:

- P-CN and C-CN: Results are similar to those described in all cases comparison. The 45m range detection allows nearly detecting all VRU with a small gain difference between 35m and 45m.
- P-CF and C-CF: Results are similar to crossing nearside scenarios.
- P-L and C-L: Results show that 45m range allows detecting more than 90% VRU at TTC 2s.The gain between 35m and 45m is small. However due to the small size of the P-L sample, results for this scenario may require to be compared with a more important sample or with other research with similar scenario definition.
- P-TL and C-TL: Results indicate that 45m range nearly allows detecting all VRU. It can be noticed that for P-TL scenario, a range of only 25m can be required. This value is lower compared to other longitudinal and crossing scenarios.
- P-TR and C-TR: Results are similar for global detection at TTC 2s with a required 45m range. It can be noticed for this scenario that with 25m detection range, the detection gain is very small and close to the 100%.

2.4.4 LTTB and t_{LTTB}

The LTTB calculus method has been described in section 2.3.2. This value corresponds to the stopping distance from the moment where brakes are triggered to the complete halt of the vehicle. For each accident in our sample in which participant kinematics is known, a LTTB value can be computed based on car's travel speed. LTTB value depends on the braking model considered. In this study, an ideal braking model has been considered with a maximum deceleration of $-8m/s^2$ (Brach and Brach 2005; Byatt and Watts 1981; Lechner and Ferrandez 1990). This ideal braking model has been compared to two other realistic models where the deceleration coefficient linearly increases until it reaches the maximum value. For the realistic models, a transient state of 0.15s and 0.3s has been considered (Saadé et al. 2019; Zhao et al. 2019b). With the LTTB information, extracting t_{LTTB} is possible by getting the time to the LTTB.

Results of this section indicate the detection rates for FOV at the time where an emergency trigger must be triggered to avoid a collision with consideration of the braking model. The detection rates for different FOV at t_{LTTB} is presented first for pedestrian and then for cyclist cases. A comparison between the ideal braking and the two other realistic models is also performed.

2.4.4.1 Pedestrian accident cases

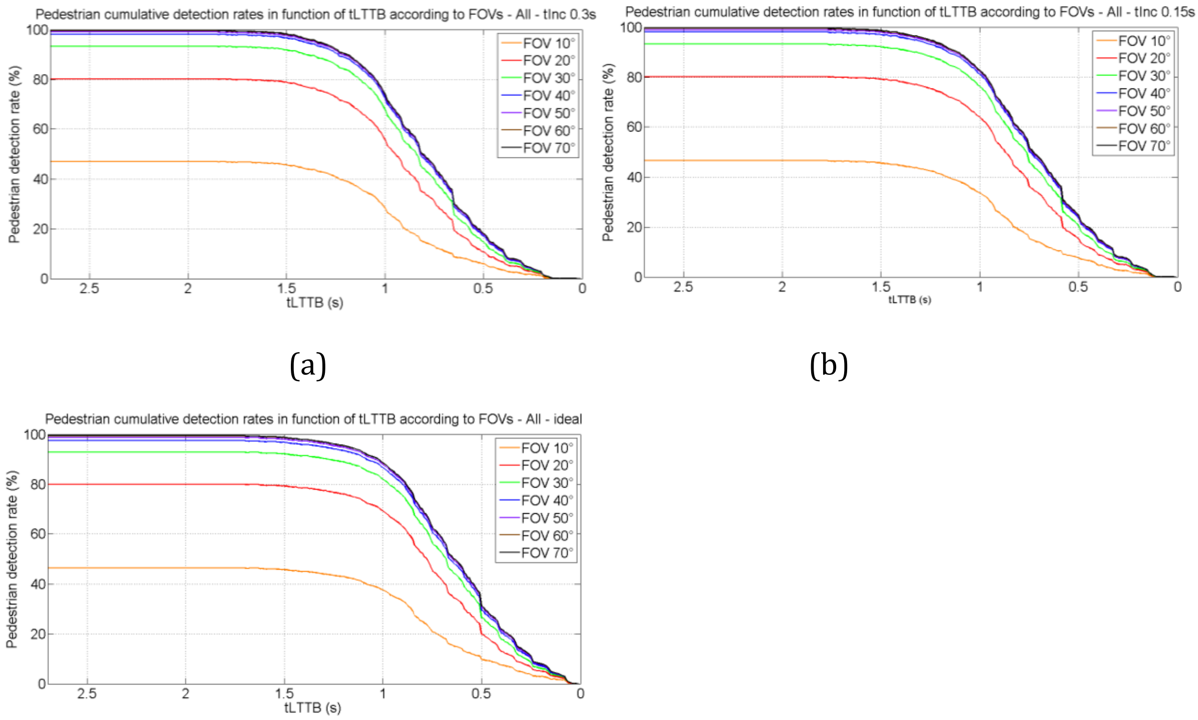
This section presents results of the detection rates at t_{LTTB} for different FOV for the three different braking models considering all pedestrian accident cases with a comparison to the ideal braking model. Then results are presented per scenario with only consideration for the ideal braking model.

Figure 68 shows the results of the detection rates at t_{LTTB} for different FOV at t_{LTTB} for the three different braking models. tInc indicates the duration of the transient state. It can be observed that in nearly all pedestrian cases, the last moment to trigger brakes is about 1.5s prior the impact. This value depends on car's travel speed. At t_{LTTB} 1.5s, it can be remarked that starting from FOV 30°, detection rates reach more than 90%. The detection rates for FOV 40° and higher are very close and only a small proportion of pedestrians are not detected with a FOV 70°. With the introduction of a transient state, a shifting appears in detection rate for low t_{LTTB} values. As the braking is less efficient compared to the ideal model, it is natural that a longer LTTB and thus a longer t_{LTTB} is required to stop the vehicle. This explains the shifting in detection rates and also why there are no detected pedestrians for low t_{LTTB} values.

Realistic braking models are compared to the ideal one. An ANOVA test with a 0.05 p-value has been performed in order to determine if statistical difference appears compared to the ideal braking model. Table 6 and Table 7 summarize the test results. For the comparison between tInc 0.15s and the ideal model, it can be remarked some statistical differences for FOV 10 and 20° for P-TL scenario. Those differences can be explained by the shifting of the LTTB value affecting low FOV values. Nevertheless, in a global way, no statistical differences appear between ideal braking model and the one with a 0.15s transient state.

The comparison between ideal braking model and tInc 0.3s reveals more statistical differences compared to tInc. Statistical differences can be observed mostly for turning scenarios as the detection angle is important due to car's trajectory. The higher is the transient state, the more difference will be observed. No statistical difference can be observed when considering all cases on our sample as turning cases constitute a minority. Table 7 summarizes the differences between the ideal model and the one with 0.3s transient state.

As no statistical difference can be observed with a transient state, the ideal braking model has been kept for later analysis.



(a) (b)

(c)

Figure 68: Pedestrian cumulative detection rates in function of t_{LTTB} for different FOV with a transient state 0.3s (a), a transient state 0.15s (b) or with ideal braking model (c)

FOV / Scenario	10	20	30	40	50	60	70	
	F	F	F	F	F	F	F	*p* value
CN	0.282	0.353	0.820	0.602	0.962	1.044	0.970	3.859
CF	1.491	0.995	0.794	0.869	0.983	1.114	0.986	3,859
L	0.611	0.657	0.657	0.657	0.657	0.657	0.657	3.859
TR	1.408	0.0003	1.726	1.714	0.328	0.354	0.354	3.859
TL	4.829	4.444	1.249	1.203	1.203	1.200	1.200	3.859
All	0.944	0.872	0.914	0.767	0.971	1.060	0.978	3.859

Rejected
Not rejected

Table 6: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.15s)

FOV / Scenario	10	20	30	40	50	60	70	
	F	F	F	F	F	F	F	*p* value
CN	0.787	2.169	2.769	2.563	3.489	3.499	3.367	3.859
CF	4.310	2.805	2.654	3.020	3.236	3.467	3.244	3,859
L	2.231	2.380	2.380	2.380	2.380	2.380	2.380	3.859
TR	19.06	30.532	5.011	5.022	0.014	2.459	2.459	3.859
TL	8.820	13.097	5.311	4.011	4.011	3.009	4.003	3.859
All	2.550	3.159	3.112	2.966	3.337	3.496	3.423	3.859

Rejected
Not rejected

Table 7: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.3s)

Pedestrian Crossing Nearside (P-CN)

Figure 69 illustrates the detection for pedestrian crossing nearside scenario. It can be observed that t_{LTTB} can mostly be found 1.5s prior the impact. FOV value of 30° and higher allow the detection of most pedestrians starting at TTC 1s. It can also be noticed that the gain starting from FOV 40° is small. Only a very small proportion of pedestrians cannot be detected in this scenario.

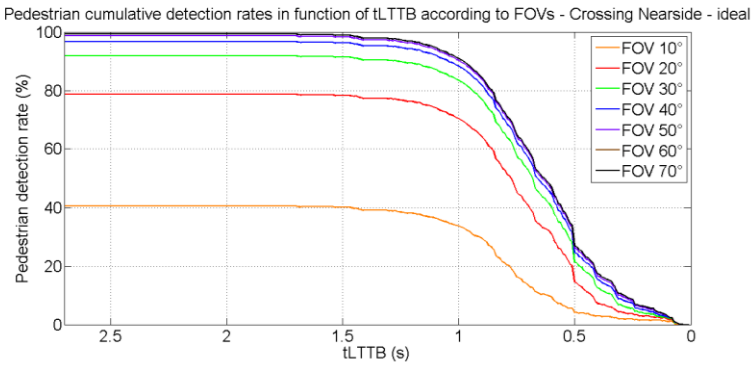


Figure 69: Detection rates at t_{LTTB} for different FOV for the pedestrian crossing nearside scenario, N = 788

Pedestrian Crossing Farside (P-CF)

Figure 70 illustrates the detection for pedestrian crossing farside scenario. It can be observed that most t_{LTTB} can be found 1.5s prior the impact. At that moment, a FOV 30° allows detecting more than 90% pedestrians. It can be noticed that detection rates for value higher than 40° have similar results. Similarly to crossing nearside scenario, only a few proportions of pedestrians cannot be detected in this scenario.

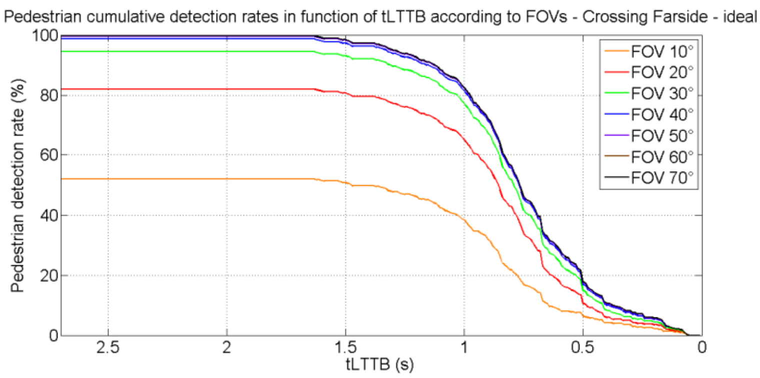


Figure 70: Detection rates at t_{LTTB} for different FOV for the pedestrian crossing farside scenario, N = 461

Pedestrian Longitudinal (P-L)

Figure 71 illustrates the detection rates for pedestrian longitudinal scenario. Similarly to crossing nearside and farside, most t_{LTTB} value can be found 1.5s prior the impact. A major difference compared to crossing scenario concerns the FOV required to reach an interesting detection rate. For this scenario at t_{LTTB} 1.5s, more than 90% pedestrians can be detected even with a very low FOV value of 10°. This can be explained by the definition of this scenario. Another interesting remark concerns the detection rate for FOV 20° and higher. It shows that all pedestrians can be detected 1.5s prior the collision and that the FOV parameter role is less important. However, due to the small size of the sample, current results have to be completed with a bigger database.

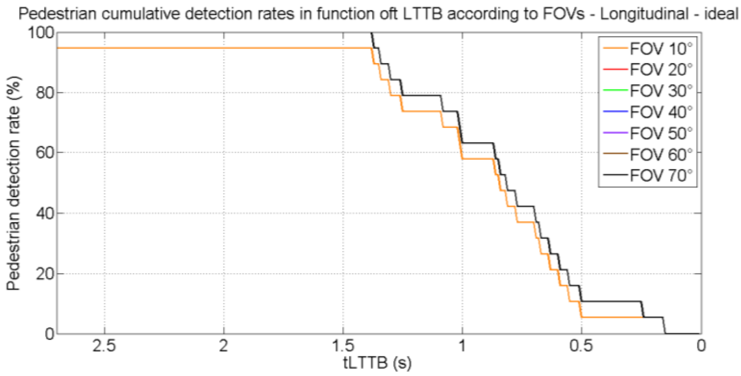


Figure 71: Detection rates at t_{LTTB} for different FOV for the pedestrian longitudinal scenario, N = 20

Pedestrian Turning Left (P-TL)

Figure 72 illustrates the detection rate for pedestrian turning left scenario. A major difference can be observed compared to crossing or to longitudinal scenario. On this scenario, most t_{LTTB} can be found less than 0.5s prior the collision. This difference may be explained by the car's speed which is slower in a turning manoeuver compared to driving in a straight road. Concerning the FOV, results are similar to crossing scenario where at t_{LTTB} 0.5s, the detection rate for 30° FOV still allow the detection of 80% pedestrians. The detection gain for FOV higher than 40° is small and only a small proportion of pedestrian cannot be detected.

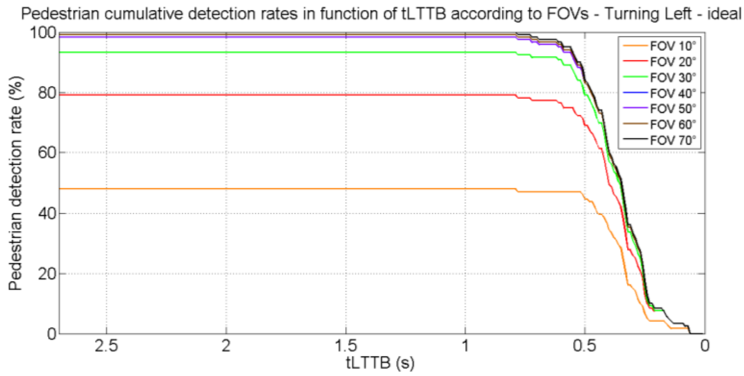


Figure 72: Detection rates at t_{LTTB} for different FOV for the pedestrian turning left scenario, N = 124

Pedestrian Turning Right (P-TR)

Figure 73 illustrates the detection rate for pedestrian turning right scenario. It can be observed that most t_{LTTB} can be found 1s prior the collision. This may be explained by slower car's speed during a turning manoeuver. For FOV 30° at t_{LTTB} 1s, more than 80% pedestrians can be detected. A detection gap can be observed between FOV 30 and 40°. Beyond 40°, the detection gain is low. Compared to other scenarios, this is the most critical scenario as this scenario has the highest proportion of pedestrians that cannot be detected even for a 70° FOV.

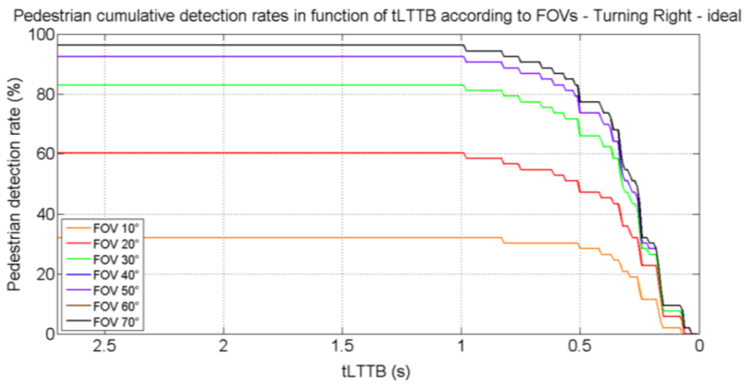


Figure 73: Detection rates at t_{LTTB} for different FOV for the pedestrian turning right scenario, N = 55

2.4.4.2 Cyclist accident cases

This section presents results of the detection rates at t_{LTTB} for different FOV for the three different braking models considering all cyclist accident cases with a comparison to the ideal braking model. Then results are presented per scenario with only consideration for the ideal braking model.

Figure 74 shows the results of the detection rates at t_{LTTB} for different FOV at t_{LTTB} for the three different braking models. tInc indicates the duration of the transient state. It can be observed that in nearly all cyclist cases, the last moment to trigger brakes is about 1s prior the impact. This value depends on car's displacement speed. It can also be noticed that with the highest detection value of 70°, 90% cyclist detection rates can be achieved at t_{LTTB} 1s. It means that there are 10% cases where cyclists cannot be detected and then, avoidance system will have no effect. At t_{LTTB} 1s, a 30° FOV is required in order to detect at least 50% cyclists.

A comparison between the ideal braking model with the more realistic two others is realized. An ANOVA test with a 0.05 p-value has been performed to determine statistical difference to the ideal model. Table 8 and Table 9 summarize the test results.

For the comparison between tInc 0.15s and the ideal model, it can be remarked no statistical difference for FOV value 50° and higher per scenario and for all scenario. There is also no difference observed for the C-L scenario whatever the FOV due to car and cyclist trajectories even with the t_{LTTB} shifting due to the transient state. It can be highlight that for low FOV value, some statistical differences can be found. Indeed, the faraway the car is in time and distance, the higher detection angle is then required to be able to detect the cyclist. Even if "small" statistical differences are observed per scenario, the differences disappear when all cases are considered for FOV 40°.

The comparison between the ideal braking model and the one with 0.3s transient state reveals high statistical differences. Indeed, the shifting induced by the 0.3s transient state appears to affect nearly all FOV. No significant difference can be observed only for FOV 70° when considering all cases even if a statistical difference exists for C-CN scenario. It can be remarked that concerning the C-L scenario, no statistical difference is observed. It might be explained by the fact that the LTTB shifting does not affect the detection FOV due to the particular scenario configuration.

Results show that the introduction of a transient state affects detection rate at t_{LTTB}. The longer is the transient state, the more difference can be observed except for longitudinal scenario.

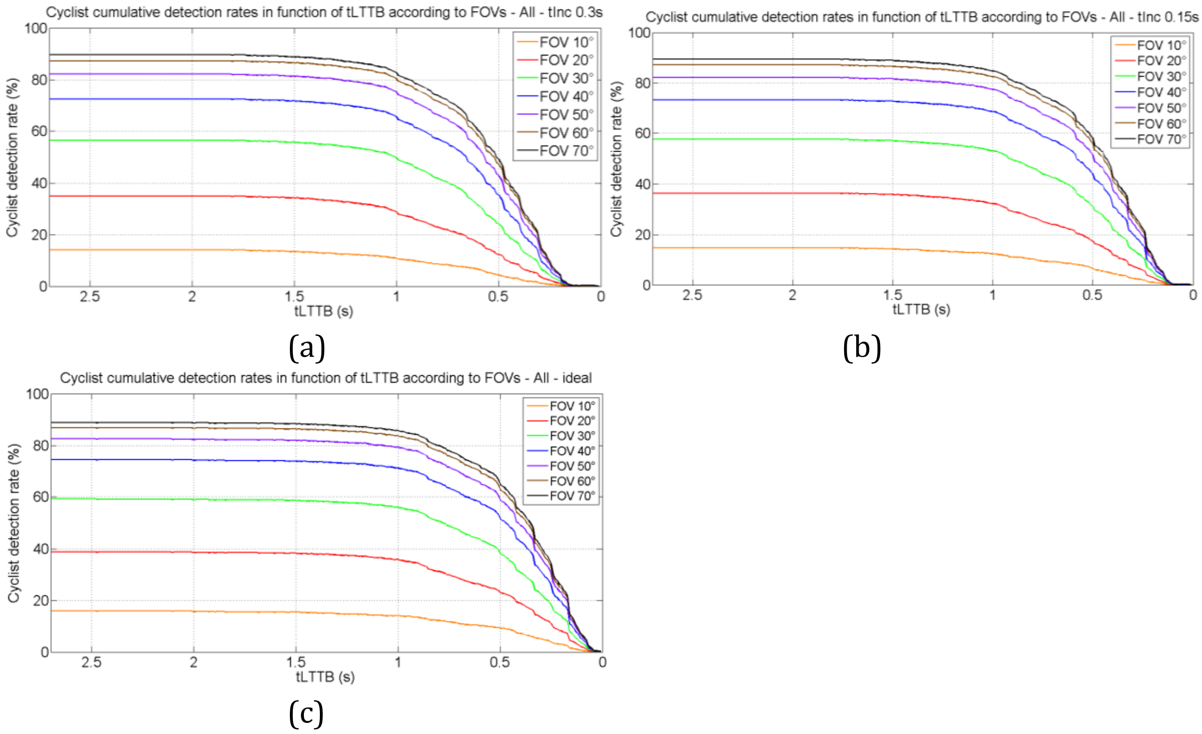


Figure 74: Cyclist cumulative detection rates in function of t_{LTTB} for different FOV with a transient state 0.3s (a), a transient state 0.15s (b) or with ideal braking model (c)

FOV / Scenario	10	20	30	40	50	60	70	
	F	F	F	F	F	F	F	p value
CN	33,556	29,249	9,715	3,994	1,950	1,751	1,112	3.859
CF	92.585	7.504	2.912	4.067	2.648	1.143	0.776	3,859
L	0,180	0,012	0,227	0,251	0,273	0,717	0,719	3.859
TR	9,396	39,285	5,323	4,250	2,389	0,978	1,225	3.859
TL	3,917	0,164	1,617	1,269	0,991	0,482	0,705	3.859
All	11.965	10.700	4.277	3.069	1.794	1.097	0.907	3.859

Rejected (white) / Not rejected (grey): not rejected cells — CN: 50, 60, 70; CF: 30, 50, 60, 70; L: 10–70; TR: 50, 60, 70; TL: 20–70; All: 40, 50, 60, 70.

Table 8: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.15s)

FOV / Scenario	10	20	30	40	50	60	70	
	F	F	F	F	F	F	F	*p* value
CN	156.268	62.378	22.593	13.937	6.541	4.936	3.910	3.859
CF	248.150	25.608	9.892	11.264	8.315	4.150	3.730	3,859
L	0.570	0.061	0.774	0.191	1.605	2.514	2.549	3.859
TR	16.335	101.538	32.774	15.626	5.546	3.613	3.744	3.859
TL	6.308	5.476	4.254	2.332	2.087	2.857	2.889	3.859
All	35.198	30.707	13.871	9.664	5.507	3.958	3.565	3.859

Rejected
Not rejected

Table 9: Results of the ANOVA test between the ideal and the realistic braking model (tInc 0.3s)

Cyclist Crossing Nearside (C-CN)

Figure 75 shows the results for cyclist crossing nearside scenario. It can be observed that most t_{LTTB} can be found 1s prior the collision. At that t_{LTTB}, 50% cyclists can be detected with a FOV 30°. It can be also remarked that detection rates are close for FOV 60 and 70°. Additionally, it can be observed that a small proportion of cyclists cannot be detected with the highest FOV value in this analysis.

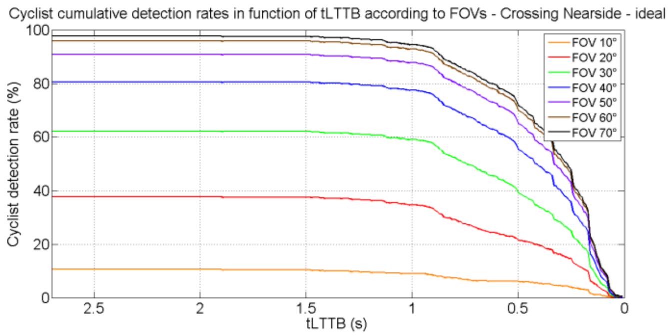


Figure 75: Detection rates at t_{LTTB} for different FOV for the cyclist crossing nearside scenario, N = 744

Cyclist Crossing Farside (C-CF)

Figure 76 shows the results for cyclist crossing farside scenario. Similarly to crossing nearside, most t_{LTTB} can be found 1s prior the collision. At that t_{LTTB}, about 60% cyclists can be detected with a FOV 30° and this rate reaches 90% with a 70° FOV. The detection difference is small between FOV 60 and 70°. Additionally, only a small proportion of cyclists cannot be detected with a 70° FOV.

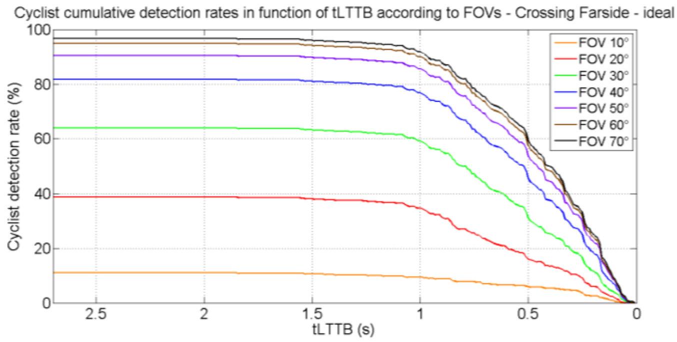


Figure 76: Detection rates at t_{LTTB} for different FOV for the cyclist crossing farside scenario, N = 504

Cyclist Longitudinal (C-L)

Figure 77 show the results for the cyclist longitudinal scenario. It can be observed that most t_{LTTB} can be found 1.5s prior the collision even if the detection rates are dispersed until 2s. This might be due to the fact that the cyclist is going in the same direction as the car. At t_{LTTB} 1.5s, close to 50% cyclists can be detected with a FOV 10°. Also the detection difference is small for high FOV values. Contrary to crossing scenario, a higher proportion of cyclists cannot be detected in this scenario close to 20%. This higher difference can be explained by cyclist position. In this scenario, the cyclist and the car are going in the same direction. However, it is possible for the cyclist in this configuration to be located behind or on car's side with a collision on car's side.

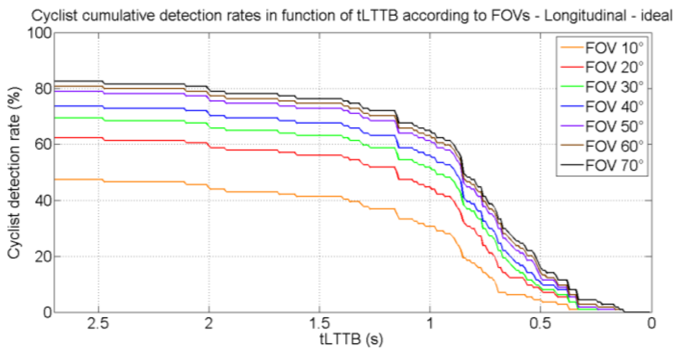


Figure 77: Detection rates at t_{LTTB} for different FOV for the cyclist longitudinal scenario, N = 120

Cyclist Turning Left (C-TL)

Figure 78 shows the results for cyclist turning left scenario. Contrary to crossing and longitudinal scenario, it can be observed that most t_{LTTB} can be found at about 0.8s prior the impact. At that t_{LTTB}, a FOV 30° is sufficient to detect at least 50% cyclists and 90% can be reached for FOV 60° and higher. The detection difference for FOV 60° and higher is small. A small proportion of cyclists cannot be detected with the highest FOV in this analysis.

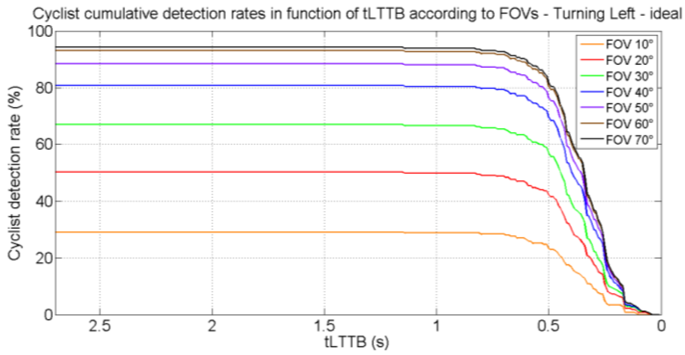


Figure 78: Detection rates at t_{LTTB} for different FOV for the cyclist turning left scenario, N = 280

Cyclist Turning Right (C-TR)

Figure 79 shows the results for the cyclist turning right scenario. Similarly to the turning left scenario, most t_{LTTB} can be found 0.8s prior the collision. At that value, a FOV 30° allows the detection of 50% cyclists and 80% of them can be detected with a FOV 70°. It can be highlight that this scenario can be as critical as the longitudinal scenario in terms of detection with 20% cyclists cannot be detected with a FOV 70°.

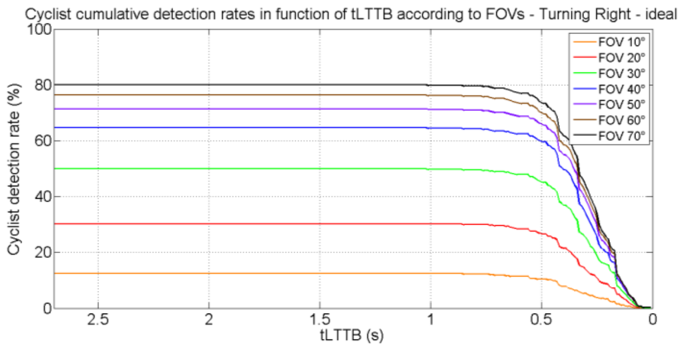


Figure 79: Detection rates at t_{LTTB} for different FOV for the cyclist turning right scenario, N = 492

2.4.4.3 Comparison between Pedestrian and Cyclist cases

This section makes a comparison considering all cases at first, and then a comparison scenario per scenario is presented.

When comparing all pedestrian and cyclist cases, a difference can be seen for t_{LTTB}. Indeed, most t_{LTTB} for pedestrians can be found 1.5s prior the impact compared to the 1s for cyclists. This difference can be explained by car's speed. As described previously, car's speed in pedestrian cases is higher (30km/h) compared to cyclists (20km/h). This way, the LTTB distance is more important and the corresponding t_{LTTB} is longer. Concerning t_{LTTB} values for pedestrians, Hamdane et al. (2015) also found similar results. In their study, most of t_{LTTB} can also be found 1.5s prior the impact even if our detection proportions differ.

The braking model comparison reveals no statistical difference even with the introduction of transient state for pedestrian cases up to 0.3s. On contrary, the same comparison made for cyclists reveals statistical differences. With a 0.15s transient state, no statistical difference can be observed for FOV 40° and higher. The transient state introduces a shifting for t_{LTTB} values and combined with cyclist position farther, low detection FOV are affected. This is confirmed for a 0.3s transient state where no statistical difference can be observed only for FOV 70°. It can be remarked that the introduction of a transient state does not affect one scenario: the longitudinal. This is due to its particular configuration: the VRU and the car going in the same direction. In that scenario, the shifting induced by the transient state has no effect on the FOV as VRU is already in the detection cone.

Even if there are detection differences in cyclist cases, the ideal braking model has been kept for later analysis as no difference has been observed for pedestrian cases and as it is difficult to choose the correct transient state.

Comparison per scenario is given next:

- P-CN and C-CN: Most t_{LTTB} values can be found 1.5s prior the impact for pedestrian cases compared to cyclists. For pedestrian cases, a FOV 40° allows more than 90% high detection rate whereas this value reaches 80% for cyclists. The gain for FOV higher than 40° for pedestrians is small whereas for cyclist gain is small for FOV higher than 60°.

- P-CF and C-CF: Comparison is similar to crossing nearside scenario. Most pedestrians t_{LTTB} can be found 1.5s prior the impact. The detection difference starting from FOV 40° for pedestrians is small whereas for cyclists, the difference starts from 60°.

- P-L and C-L: For both VRU, most t_{LTTB} can be found 1.5s prior the collision. No detection difference can be observed for FOV 20° and higher for pedestrian cases whereas for cyclist's ones the difference per FOV is small between each FOV values. It can also be remarked that all pedestrians can be detected whereas a non-neglected proportion of cyclists cannot be detected prior the collision. However this observation for pedestrians has to be considered carefully as the size of the sample is small. This way, cyclist longitudinal scenario is a critical scenario in terms of detection.

- P-TL and C-TL: For both VRU, most t_{LTTB} can be found 0.8s prior the impact. The gain difference is small starting from FOV 40° for pedestrian cases whereas for cyclists, this difference starts from FOV 60°. A small proportion of cyclists cannot be detected prior the impact.

- P-TR and C-TR: Most t_{LTTB} values can be found 1s prior the collision. For both VRU, the gain difference is important starting for FOV 60° and higher. It can also be highlighted that a non-neglected proportion of cyclists cannot be detected prior the collision. Similarly to the cyclist longitudinal scenario, this scenario is critical in terms of detection.

2.4.5 Visibility duration before the t_{LTTB} (tvisible-t_{LTTB})

This section presents the results concerning the visibility of the VRU prior t_{LTTB} if the VRU is not hidden at t_{LTTB} or the late delay if the VRU is occluded at t_{LTTB}. Results is presented for all cases and then per scenario with a comparison.

2.4.5.1 Pedestrian accident cases

Figure 80 represents the rate of visible pedestrians at tvisible-t_{LTTB}. tvisible-t_{LTTB} equals to 0 corresponds to the proportion of detected pedestrians at t_{LTTB}. tvisible-t_{LTTB} positive values indicate that the pedestrian is visible prior the t_{LTTB}. This amount of time can correspond to the available time for an AEB system. On the opposite, tvisible-t_{LTTB} negative values represent a delay in detection to the t_{LTTB}. A value of -1s for tvisible-t_{LTTB} indicates that the system detects the pedestrian with 1s delay resulting in mitigation at best. It can be observed that about 80% pedestrians can be detected 1s prior the t_{LTTB} with a FOV 70°. This rate falls to 60% for a FOV 20°. 70% pedestrians can be detected 2s prior the t_{LTTB} with a 70° FOV and a little less than 60% with a 20° FOV. On the opposite, this figure indicates that in less than 10% cases, the pedestrian is detected 1s too late allowing only mitigation at best. It can also be observed that the gain starting from FOV 40° is small for higher FOV values.

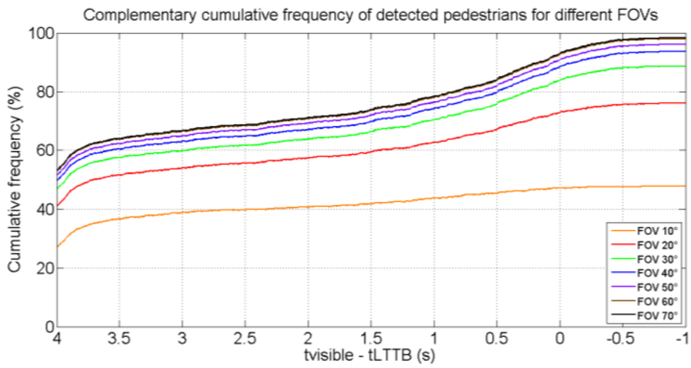


Figure 80: Detection rates at tvisible-t_{LTTB} for all pedestrian cases, N = 1509

Pedestrian Crossing Nearside (P-CN)

Figure 81 shows the tvisible-t_{LTTB} detection rates for pedestrian crossing nearside scenario. It reveals that a FOV 70° allows the detection of 70% pedestrians 1s prior the t_{LTTB} whereas for a FOV 20° this rate falls to a little lower than 60%. The detection rate reaches close to 60% with a FOV 70° when the pedestrian is detected 2s prior the t_{LTTB}

and falls to 50% for a 20° FOV. Similarly to crossing nearside, about 10% pedestrians are detected 1s too late to avoid the collision for 70° FOV.

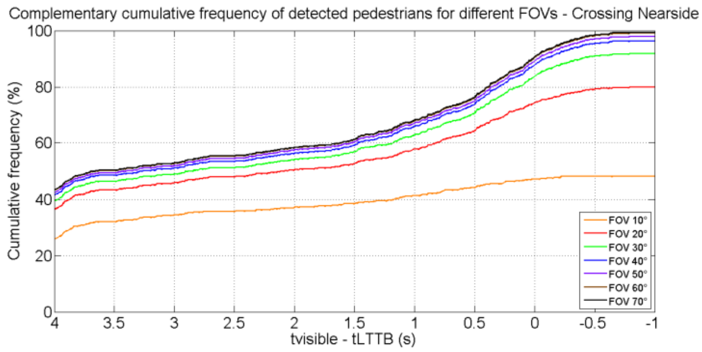


Figure 81: Detection rates at tvisible-t_{LTTB} for pedestrian crossing nearside cases, N = 788

Pedestrian Crossing Farside (P-CF)

Figure 82 shows the tvisible-t_{LTTB} detection rates for pedestrian crossing farside scenario. It reveals that a 70° FOV allows detecting close to 90% pedestrians 1s prior the t_{LTTB} and a little less than 80% with a FOV 20°. A 70° FOV still allow the detection of more than 80% pedestrians 2s prior the t_{LTTB} and 70% with a FOV 20°. On the opposite, it can be observed that there are about 5% cases where pedestrians are detected 1s too late with a 70° FOV. Starting from FOV 40°, the gain with higher FOV is very close.

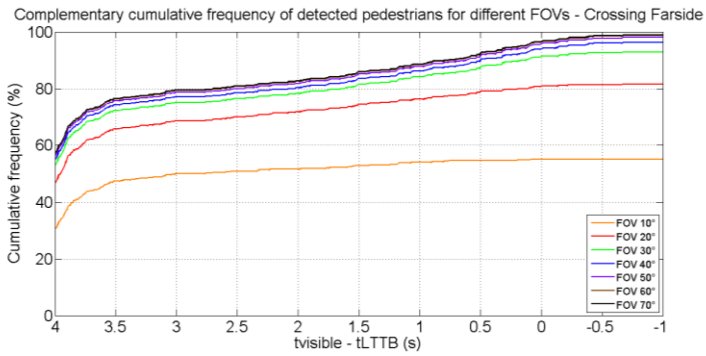


Figure 82: Detection rates at tvisible-t_{LTTB} for pedestrian crossing farside cases, N = 461

Pedestrian Longitudinal (P-L)

Figure 83 shows the tvisible-t_{LTTB} detection rates for pedestrian longitudinal scenario. It can be observed that for all FOV values more than 90% pedestrians can be detected 1 or 2s prior the t_{LTTB}. No pedestrian is detected after the t_{LTTB} showing that all accidents in this scenario can potentially be avoided.

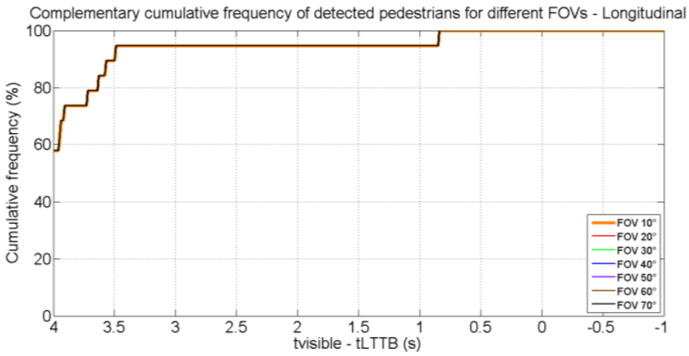


Figure 83: Detection rates at tvisible-t_{LTTB} for pedestrian longitudinal cases, N = 20

Pedestrian Turning Left (P-TL)

Figure 84 shows the tvisible-t_{LTTB} detection rates for pedestrian turning left scenario. It can be observed that more than 90% pedestrians can be detected 1s prior the t_{LTTB} with a FOV 70° and more than 50% with FOV 30°. This rate decreases a little higher than 2s before the t_{LTTB}. Even with the highest 70° FOV in this study, it can be noticed that there are about 5% cases where pedestrians are not detected.

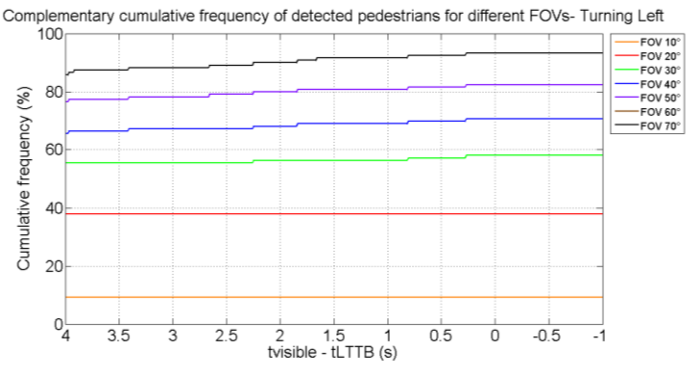


Figure 84: Detection rates at tvisible-t_{LTTB} for pedestrian turning left cases, N = 124

Pedestrian Turning Right (P-TR)

Figure 85 shows the tvisible-t_{LTTB} detection rates for pedestrian turning right scenario. It can be observed that 90% pedestrians are detected 1s prior the t_{LTTB} with a FOV 70° and more than 60% with a FOV 30°. This rate falls to about 80% for FOV 70° more than 2s prior the t_{LTTB} and to more than 60% with a FOV 30°. Similarly to turning left scenario, there are about 5% cases where pedestrians cannot be detected even with a 70° FOV.

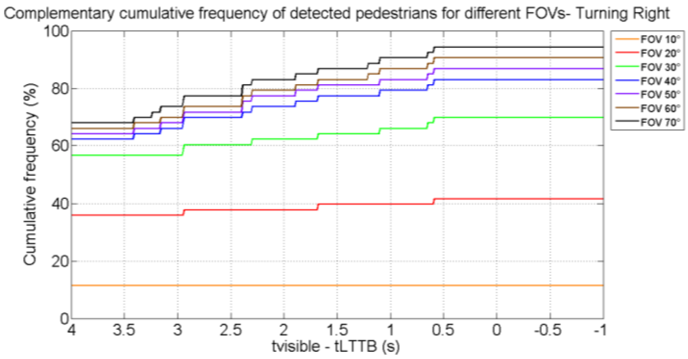


Figure 85: Detection rates at tvisible-t_{LTTB} for pedestrian turning right cases, N = 55

2.4.5.2 Cyclist accident cases

Figure 86 shows the rate of visible cyclists at tvisible-t_{LTTB}. It can be observed that close to 80% cyclists can be detected with a 70° FOV and 50% with a FOV 40° 1s prior the t_{LTTB}. This rate falls to 70% for FOV 70° 2s prior the t_{LTTB}. On the opposite only a few percentages of cyclists are detected 1s too late to avoid a collision. It can be highlighted that there are about 10% accident cases where cyclists cannot be detected prior the impact with a 70° FOV.

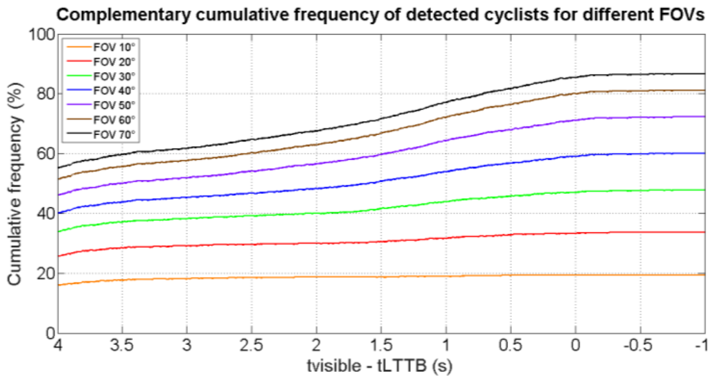


Figure 86: Detection rates at tvisible-t_{LTTB} for all cyclist cases, N = 2261

Cyclist Crossing Nearside (C-CN)

Figure 87 shows the tvisible-t_{LTTB} detection rates for cyclist crossing nearside scenario. It can be observed that about 70% cyclists can be detected 1s prior the t_{LTTB} with a FOV 70° and more than 50% with FOV 40°. This rate falls a little less than 60% 2s before the t_{LTTB} with FOV 70°. Even with the highest 70° FOV in this study, it can be noticed that there are about 10% cases where cyclists are not detected.

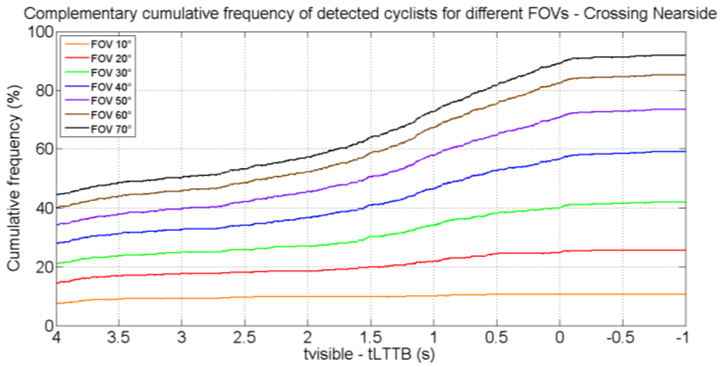


Figure 87: Detection rates at tvisible-t_{LTTB} for cyclist crossing nearside cases, N = 744

Cyclist Crossing Farside (C-CF)

Figure 88 shows the tvisible-t_{LTTB} detection rates for cyclist crossing farside scenario. It can be observed that more than 80% cyclists can be detected 1s prior the t_{LTTB} with a FOV 70° and 60% with FOV 40°. This rate decreases to a little less than 80% 2s before the t_{LTTB} with FOV 70°. Even with the highest 70° FOV in this study, it can be noticed that there are about 10% cases where cyclists are not detected.

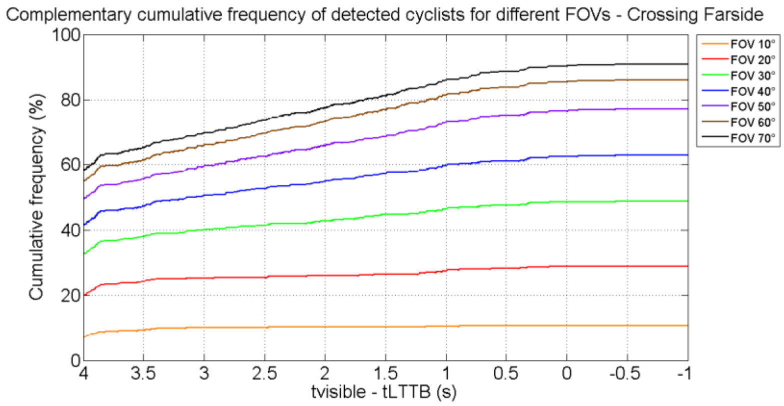


Figure 88: Detection rates at tvisible-t_{LTTB} for cyclist crossing farside cases, N = 504

Cyclist Longitudinal (C-L)

Figure 89 shows the tvisible-t_{LTTB} detection rates for cyclist longitudinal scenario. It can be observed that more than 80% cyclists can be detected 1s prior the t_{LTTB} with a FOV 70° and that this rate is also the same at t_{LTTB} 2s. Whatever the FOV value, the gain between each FOV is small starting from 20°. Even with the highest FOV in this study, it can be noticed that there are about 15% cases where cyclists are not detected.

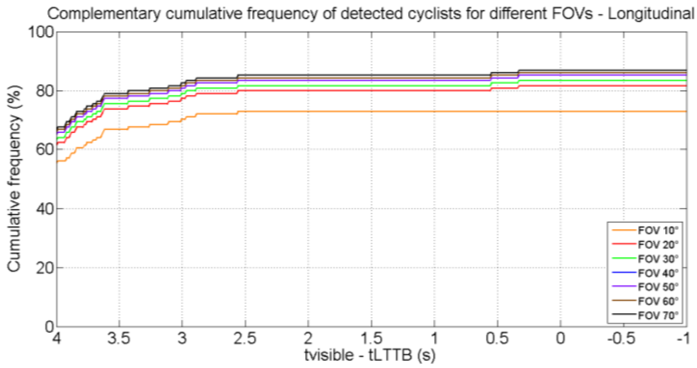


Figure 89: Detection rates at tvisible-t_{LTTB} for cyclist longitudinal cases, N = 120

Cyclist Turning Left (C-TL)

Figure 90 shows the tvisible-t_{LTTB} detection rates for cyclist turning left scenario. It can be observed that more than 80% cyclists can be detected 1s prior the t_{LTTB} with a FOV 70° and 50% with a FOV 20°. Even with the highest FOV in this study, it can be noticed that there are about 10% cases where cyclists are not detected.

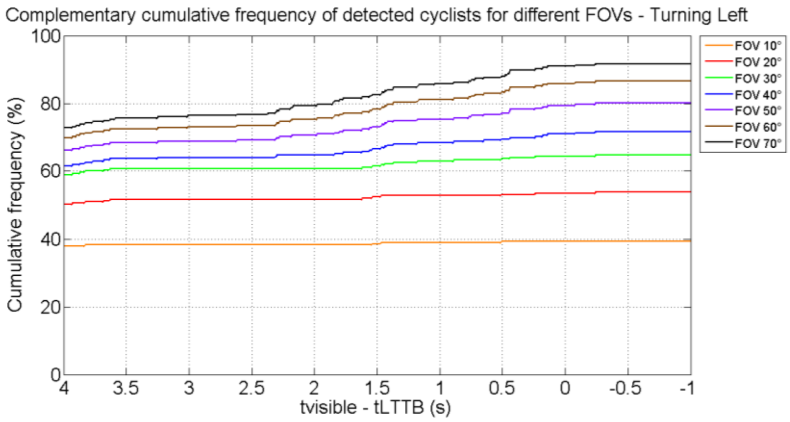


Figure 90: Detection rates at tvisible-t_{LTTB} for cyclist turning left cases, N = 280

Cyclist Turning Right (C-TR)

Figure 91 shows the tvisible-t_{LTTB} detection rates for cyclist turning right scenario. It can be observed that less than 80% cyclists can be detected 1s prior the t_{LTTB} with a FOV 70° and close to 50% with a FOV 40°. Even with the highest FOV in this study, it can be noticed that there are about 20% cases where cyclists are not detected. It reveals that this scenario is the most critical among the 5 identified scenarios in this study.

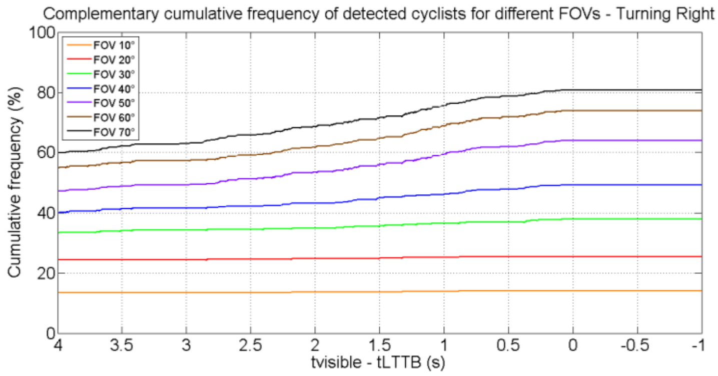


Figure 91: Detection rates at tvisible-t_{LTTB} for cyclist turning right cases, N = 492

2.4.5.3 Comparison between Pedestrian and Cyclist cases

Detection curves evolve in a similar way for both pedestrian and cyclist cases with slight slope differences. In pedestrian cases, detection can be close to 100% contrary to cyclists where detection is limited to less than 90%. It can be observed that less than 80% pedestrians and cyclists can be detected with a 70° FOV 1s prior the t_{LTTB}. Still close to 70% pedestrians and cyclists can be detected with a FOV 70° 2s prior the t_{LTTB}. It can also be observed that in order to reach at least 50% detection at tvisible-t_{LTTB} equal to 1s, a minimum FOV of 20° is required for pedestrians and 40° for cyclists. This reveals that an active safety system like an AEB has some time to detect, analyze and trigger an action before it is too late in order to avoid a collision. Contrary to pedestrian cases, there is a non-neglected proportion of cyclist cases where the cyclist cannot be detected even with a FOV 70°.

Comparison per scenario is given below:

- P-CN and C-CN: It can be observed that curves evolve in a similar way for pedestrians and cyclists. Detection gain between different FOV is small for pedestrian cases contrary to cyclists with higher detection gap between each FOV. At least 1s prior t_{LTTB} is available with a 70° FOV either for pedestrian or cyclist cases and close to 90% pedestrians and cyclists can be detected with 70° FOV at t_{LTTB}.

- P-CF and C-CF: Results are similar to crossing nearside concerning curves evolution and gain gap between FOV with differences only on detection proportions. For both pedestrian and cyclist crossing farside scenarios, detection rates reach close to 90% for FOV 70° 1s prior the t_{LTTB} compared to the 70% for crossing nearside. This higher value can be attributed to the occlusion factor. Indeed, in accidents classified in the crossing nearside scenario, there are more cases where an object of the surrounding environment has hidden the VRU prior the collision. The result of this analysis is given in 3.31.

- P-L and C-L: It can be observed that all pedestrians can be detected close to 1s prior the t_{LTTB} contrary to cyclists where the detection is limited to 90% at that same t_{LTTB}. It can be highlighted that the FOV effect on detection is null for pedestrian cases and very limited on cyclist ones due to the scenario configuration. A reminder concerns the size of the P-L which is small and may require a higher sample in order to extract robust conclusion.

- P-TL and C-TL: Similar results can be found for pedestrian and cyclist cases with proportion difference. The detection rate is 90% 1s prior the t_{LTTB} for both VRU. About 10% pedestrians and cyclists are not detected prior the t_{LTTB}. The detection proportion is similar for FOV 40°.

- P-TR and C-TR: Detection curve forms are similar. Detection rate reaches 90% with a 70° FOV for pedestrian cases and close to 80% for cyclists 1s prior the t_{LTTB}. This rate is decreased by about 10% for 2s tvisible-t_{LTTB}. The proportion of undetected pedestrian for this scenario is similar to the proportion of pedestrian turning left scenario. However an important gap can be noticed between pedestrians and cyclists with 5% for pedestrians not detected at least 1s after the t_{LTTB} and up to 20% for cyclists. Thus, the cyclist turning right scenario appears to be one of the most challenging scenario.

2.5. Conclusion

Here is the summary of the main results previously described in this chapter.

Five main scenarios have been identified from literature: crossing nearside, crossing farside, longitudinal, turning left and turning right. Accident cases from our two databases have been classified into one of the five previously identified scenarios or into the "Others" group based on a decision tree. Table 10 summarizes the proportion of accidents for each different scenario of our sample for pedestrian and cyclist cases.

Scenario / VRU	Crossing Nearside	Crossing Farside	Longitudinal	Turning Left	Turning Right	Others
Pedestrian (%)	52	31	1	8	4	4
Cyclist (%)	33	22	5	12	22	6

Table 10: Proportion of accident cases classified into the different identified scenarios

From the accident kinematic reconstructions of more than 2200 cyclist cases and 1500 pedestrian cases, the main results are summarized in Table 11.

Pedestrian accident kinematics	Cyclist accident kinematics
- few pedestrians are located in car's front path until 1s before the impact - most pedestrians are 20m far ahead the car and ±3m laterally 1s before the impact - car's average approach speed : 30km/h - pedestrian speed: 5km/h - 51% brake activation on all cases; about 90% brakes activated 1s prior the impact	- few cyclists are located in car's front path until 1s before the impact - most cyclists are 20m far ahead from the car and ±10m laterally 1s before the impact - car's average approach speed: 20km/h - cyclist's speed: 15km/h - 33% brake activation on all cases; less than 80% brakes activated 1s prior the impact

Table 11: Main results on accident kinematic reconstruction analysis

The FOV analysis reveals that 90% pedestrians can be detected at TTC 2s prior the collision with a 40° FOV whereas a 70° FOV is required for cyclists to reach the same detection rate. In longitudinal scenario, it can be noticed that FOV has no effect on detection rates for pedestrian scenario and very little effect on cyclists. The analysis also reveals that C-TR scenario is one critical scenario with the lowest detection rate (80%) even with a FOV 70°.

The range analysis shows that a 45m range is sufficient to nearly detect all pedestrians and cyclists 2s prior the collision.

Different braking models have been compared for the detection at the t_{LTTB} in order to determine if statistical difference can be found. The comparison of a braking model with a transient state of 0.15s and 0.3s to the ideal model reveals no statistical difference for pedestrian accidents. Most t_{LTTB} can be found 1.5s prior the collision. At that t_{LTTB}, a 30° FOV is sufficient to detect 90% pedestrians.

On cyclist cases, the comparison reveals some differences. With a transient state of 0.15s, statistical difference can be found for FOV 30° and lower on all cases. With a transient state of 0.3s, statistical difference can be found for every FOV except for FOV 70°. Most t_{LTTB} can be found 1s prior the collision. At that t_{LTTB}, a FOV 70° allows the detection of 90% cyclists.

Even if differences can be found on cyclist cases, it has been decided to keep the ideal braking model for further analysis. This choice is motivated by the possibility to make comparison between pedestrian and cyclist results for AEB characteristics using the same braking model. It is also used later in chapter 4 for the final outcome of FCW effect on real accident case simulations between pedestrians and cyclists. Moreover, because the ideal braking can be considered as the better, this choice will give us the better benefits on real accidents. So the simulations will provide a maximal optimistic benefits.

The analysis of the available visibility time of VRU prior or after t_{LTTB} has also been performed. This analysis reveals for pedestrian cases that 80% pedestrians can be detected with a 70° FOV 1s prior the t_{LTTB}. This rate falls to 70% 2s prior the t_{LTTB}. It can also be highlighted that in longitudinal scenario, detection rate can go up to 90% with a 20° FOV 2s prior the t_{LTTB}.

Concerning cyclist cases, 80% cyclists can be detected with a 70° FOV 1s prior the t_{LTTB} and this rate falls to 70% 2s prior the t_{LTTB}. For cyclist longitudinal scenario, it can be observed that a FOV 20° allows the detection of about 75% cyclists compared to the 80% for a 70° FOV.

Available time prior the t_{LTTB} has been analyzed. This information indicates the amount of time a system can have from VRU first detection in order to collect, analyze and trigger an appropriate action. In the case of an AEB, it indicates the processing time the system has before triggering. However, in the case of a FCW, this duration can give an indication of when a signal can be given and to how much time a driver has to react to it. The main difference between an AEB and a FCW concerns the triggering of the manoeuver. In the case of an AEB, the trigger is performed by the safety system contrary to the FCW where human is in the center of the loop. Thus if it is intended to trigger a reaction from driver in order to avoid a collision in the case of the FCW, the available time prior the t_{LTTB} becomes a critical parameter. Triggering a signal to alert driver before a collision is possible. However, as the objective is to avoid a collision, the signal has to be given before the t_{LTTB} as it can be computed in this study.

Thus, an early detection of the VRU is first required for the system to be efficient. Then, the question is to determine when to alarm the driver prior the t_{LTTB} in order to give him/her sufficient time to react. Driver reaction to a signal may vary significantly depending in particular on the signal and on drivers. The signal requires to be appropriate to trigger an emergency reaction. However, depending on the driver profiles, finding the appropriate setting is a difficult task. This is why, driver trust, acceptability and acceptance are important. Even if a system is designed to improve safety, it might not be adopted by user if there is no drivers' final acceptance. Next chapter presents a driving simulator study in order to evaluate drivers' response to a FCW.

3. Drivers' response to a FCW

A driving experiment is performed in order to find a suitable driver model reproducing the driver response to a FCW in case of an imminent collision. Reproducing accident scenarios is also challenging. With the help of in-depth investigation team collecting as much and precise data relative to an accident, accident scenarios have been recreated in a driving simulator. It is possible to recreate the surrounding infrastructure with buildings, roads, the weather conditions and also to animate a VRU involved in the accident as in a real accident. However in each accident there is one thing that represents a challenge to reproduce: driver behavior. Indeed, in each accident, a specific driver is involved and reacted in a particular way leading to an accident. Even if all accident circumstances can be reproduced, reproducing drivers' exact behavior at the moment of the accident is not possible as individuals are different. Depending of the driving experience, of the perception of the scene none will react in the same way. Thus reproducing driver behavior may require the introduction of a secondary task. Introducing a secondary task might help getting closer to driver behavior as in the original accident but is not a guarantee.

3.1 Objectives of the driving simulator campaign

In order to evaluate the potential benefit of a FCW, it is important to determine its effect on drivers. The purpose of the driving simulator campaign is to extract drivers' behavior towards a FCW signal triggered in the case of a collision with a VRU. The extracted results will be introduced in a simulation software in order to determine the new kinematics thanks to the FCW intervention as shown in Figure 92. Results concern the drivers' reaction time after a warning is emitted: the perception reaction time (time to release the gas pedal after a hazard is seen), the movement time (time to release the gas pedal to start depressing the brake pedal) and also drivers' feedback considering the presented FCW signal and trigger time (see Figure 93).

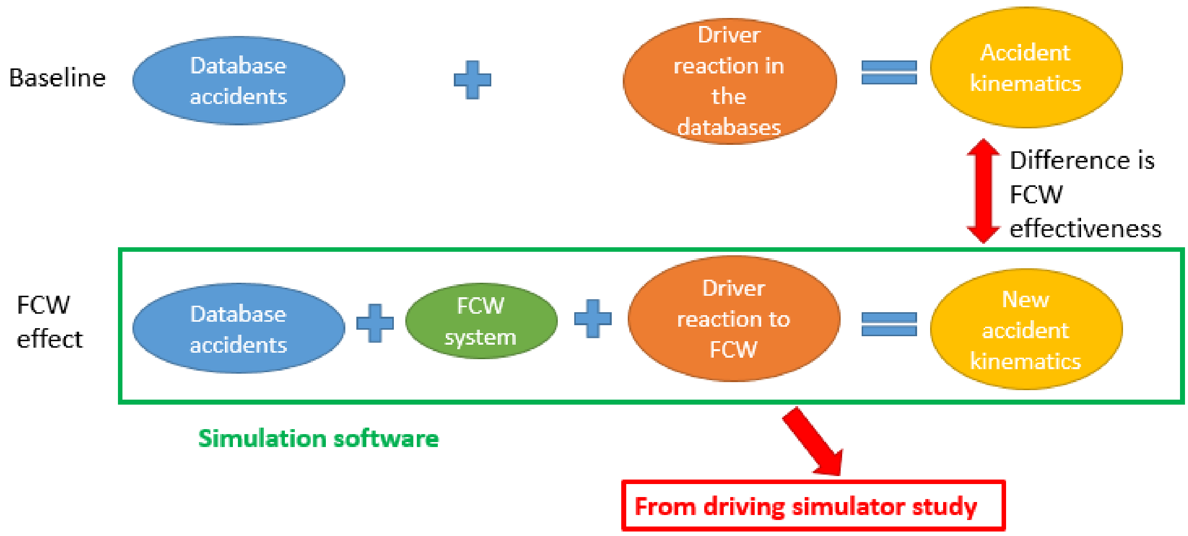


Figure 92: Purpose of the driving simulator campaign

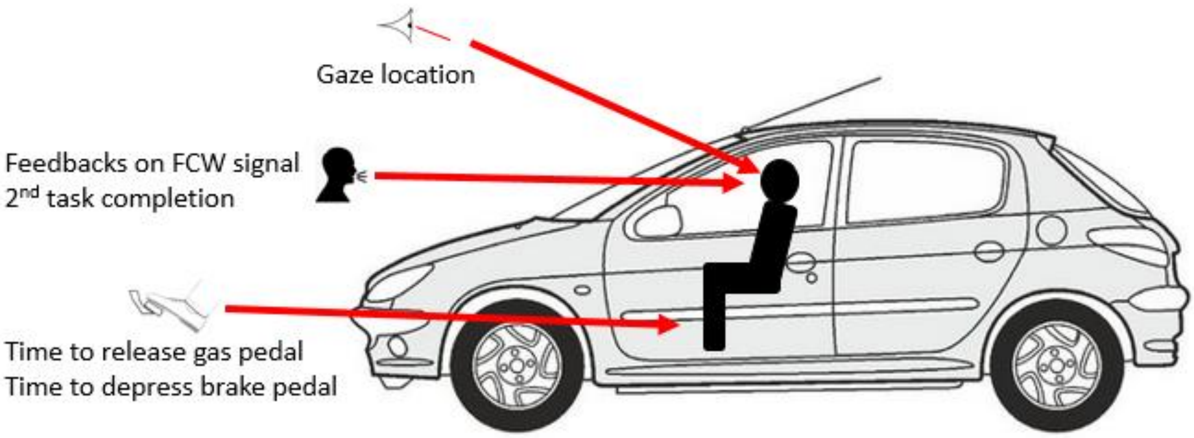


Figure 93: Results from the driving simulator experiment

Prior the setting up of the experimental campaign that is described in this chapter, one preliminary test has been performed. It aims at the selection of scenarios for the main campaign, the set-up and the result analysis method. The appendix A describes in details the test protocol and results. Nevertheless, the main interest points of this test are summarized here.

From the preliminary test, two scenarios have been considered, a Pedestrian Crossing Nearside (P-CN) and a Cyclist Longitudinal (C-L) on a sample of 20 participants. The choice of those two scenarios was motivated by the fact that crossing nearside was the most frequent scenario and that both scenarios were proposed for Euro NCAP test protocol for AEB (Euro NCAP 2017b). It was also important to determine the total experiment duration for one participant. This first test results show that a secondary task is required in order reproduce conditions similar to what happen during the real accident.

It reveals that the mean experimental duration for one participant is about 2 hours and that experiencing two scenarios is possible without effect either on scenario order nor reaction time on drivers. After this test, it was decided to remove crossing scenarios from the main experiment campaign as these scenarios were well-explored in Euro NCAP test protocol and to focus more on under-investigated scenarios like turnings. It was also decided to keep the longitudinal scenario as this scenario appears in FCW test protocol (Euro NCAP 2018).

The very first participants of our main campaign experimented a Turning Right with Pedestrian coming from the Right (TR-PR), a Turning Left with Cyclist coming from the Right (TL-CR) scenarios. At the beginning of the main experiment, it appears that reproducing turning accidents without distracting drivers lead to no accident situations. Early results for the two turning scenarios reveal no accident leading to the conclusion that a secondary task was required. Some participants also experienced the Cyclist Longitudinal scenario (C-L). Their runs help in determining the instructions given prior driving the C-L scenario and also adjusting the task trigger timing. More details are given in the secondary task section and in the data matrix section.

The introduction of a distracting task has to be considered carefully. In a turning situation, it is not possible to visually distract drivers as they need to look to the direction they are heading to. In a longitudinal situation, it is possible to visually distract drivers if they are already driving in a straight line (Alonso et al. 2012). However, using a distraction task that does not divert drivers' attention off the road in longitudinal situation may not allow recreating the dangerous situation to correctly evaluate the FCW effect. Thus depending on the task and also on the driving configuration, the same task cannot be used. Initially, the 1-back task described by Mehler et al. (2011) was considered for longitudinal scenarios with adjustments. The task consists for participants to repeat loud the number before the last number heard. However as reported by Merat et al. (2015) this task is considered as an easy task and it has been decided to increase the difficulty of this task. First, in order to become a visually-cognitive task, the digit series is visually displayed on a screen inside the car instead of being verbally given. Second, participants were asked to memorize the whole digit series and to repeat it loud just after the end of the display in order to increase the task difficulty and also to avoid participants to anticipate the scenario situation.

For turning situation, an audio-cognitive task has been introduced. Turner and Engle (1989) proposed an operation stimuli consisting of verifying the answers to strings of arithmetic operations and recalled the digit answers to the right whether the answer was correct or not. In a similar way, we proposed an audio-cognitive task consisting of single digit multiplication combined with memorization which is described later in the secondary task section.

3.2 Driving simulator

3.2.1 General description

The driving simulator environment contains 6 modules as illustrates in Figure 94:

- The driving cabin: it is the link between the driver and the simulator. A vehicle commonly found on the roads is usually selected. The cabin is fully instrumented: sensors measure inputs from the brake and gas pedals, from the steering column and from the gear shift. Driver's controls and dashboard warnings are also considered.

- The acquisition and control device receives inputs from the sensors and optical encoders of the driving cabin. It controls speedometer and round per meter actuators, and transmits the measured information to the computer calculating the vehicle dynamic model.

- The vehicle model receives inputs from the acquisition and control card and takes into account the mechanical behavior of several vehicle components to compute in real-time the vehicle characteristics in a traffic model.

- The traffic model ARCHISIM is able to simulate in real-time a traffic environment involving tens of vehicles. ARCHISIM is also able to host a driving simulator, and can integrate a real vehicle cabin as a particular vehicle of the traffic simulation.

- The visual display uses five projectors associated with five screens. The simulator displays the view that could be seen from any vehicle of the simulated traffic and hence, from the vehicle represented by the real vehicle cabin. The computation of the 3D environment is performed by an ONYX workstation, which is specialized in 3D graphic applications. A rear projection system is set up using LCD screens located on the side of the vehicle. Using the side mirrors of the vehicle, the driver will be able to see the rear driving environment displayed by the LCD screens. Computation of the 3D images is performed by a PC running under windows and used OpenSceneGraph (open source 3D graphics application programming interface).

- Sounds from the vehicle engine and surrounding traffic environment are simulated. Quadriphonic and spatialized sounds are reproduced.

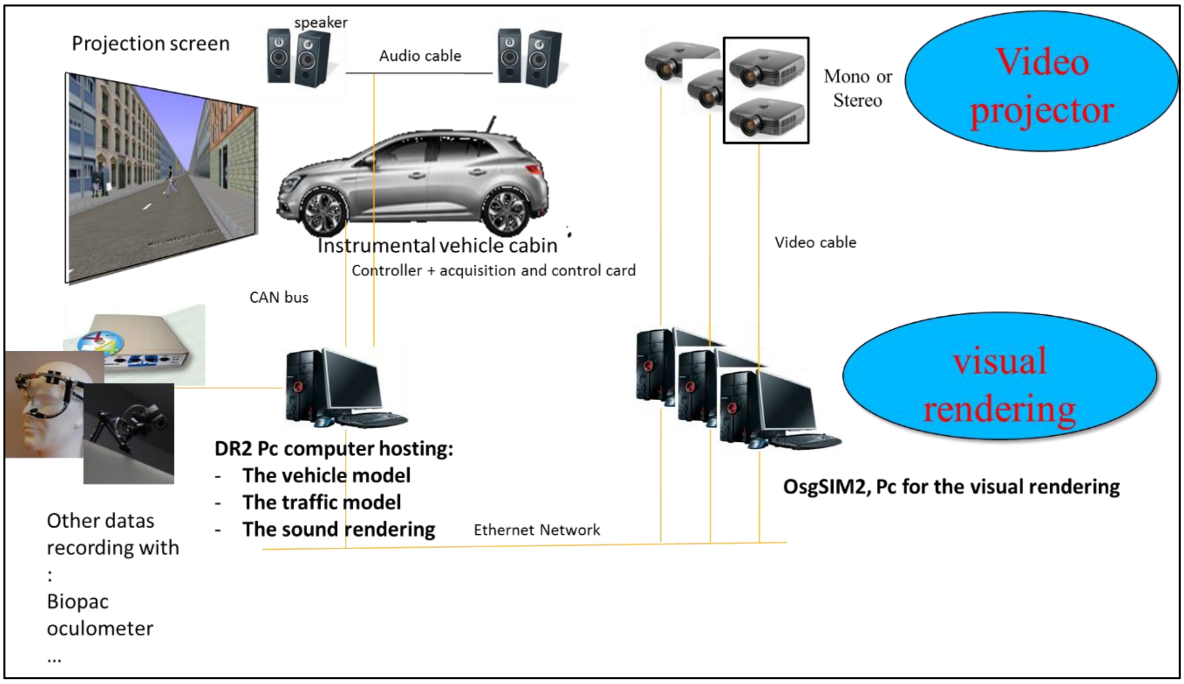


Figure 94: General organization of LMA current simulator

In Salon-de-Provence, the LMA driving simulator is a fixed-base simulator (Figure 95), equipped with an instrumented vehicle cabin (Renault Megane) including all the basic controls and a classical dashboard.

It is equipped with parallel architecture multi-actors for the simulation of the traffic (ArchiSim) and the database resulting from the software SIM^2 (Espié et al. 2005). The "architecture" ArchiSim is based on the model of simulation of traffic DR2 (management of “intelligent” vehicles and “automat” vehicles which the behavior is defined by scripts for every scenario, the simulation being generated by limited and spatial sensors of traffic) and on the loop of 3D display OSGSIM2.

The road visual scene is displayed on 5 screens representing a 200° horizontal field of vision and a 40° vertical field of vision. The dimensions and the resolution of each screen are 1.80m X 1.35 m and 1280 X 1024 pixels, respectively. The central screen is 2.20 m from the driver and the average distance (depending on the size of the subject) between the ground and the eyes of the driver is equal to 1.20 m.

The values of acceleration, in braking and transverse (direction) of the simulator are those of an average vehicle. They are not returned physically to the driver since the simulator is a fixed-base one. Controller and CAN Buses are installed on the simulator in order to record these values in real time.

The vehicle has a manual gear box and rear view mirrors. The rear view mirrors are operational thanks to screens fixed outside on the doors and inside the vehicle.

A sound in quadraphonic comes through loudspeakers into the cabin with internal noises of the vehicle (engine, bearing, starter) and external spatialized traffic noise.

The equipment of the simulator was developed in Salon de Provence. Data processing, electronics and the software are developed by the COSYS-LEPSIS and remain their property.

Figure 95: Driving simulator

3.2.3 Video recording

The simulator gives the opportunity of video recording (Figure 96) thanks to three cameras which record the face of the driver, the pedals and the screens in front of the simulator so to be able to supervise the state of the driver (wellness and control behavior) and the good application of the instructions.

Figure 96: Example of video recordings

3.2.4 Additional elements

Other elements can be found on the driving simulator. They concern mainly the integration of secondary tasks, the adaptation of the car braking model and the connection of an eye tracker.

A secondary task has been expected. Distract participants is necessary in order to recreate accident circumstances. Thus, a visual-cognitive task has been implemented through the installation of screen inside the vehicle. This screen is linked to the driving simulator and is synchronized with it. The screen is installed in a similar place as an on-board computer (see Figure 97).

Figure 97: Screen for visual-cognitive task

- The objective of the driving simulator study is to evaluate drivers' reaction to the FCW. Thus, it appears interesting to use an eye tracker system to observe FCW influence on their behavior. The material used is a Facelab tracking device (Seeing Machines, 2020), with two separate cameras which can have various positions (see Figure 98). It tracks eye positions, head movements and other facial features indicating where the gaze is located. Data collected with this device are coordinates [X, Y] associated to a time T of a zone that needs to be pre-defined prior data acquisition.

Figure 98: Facelab eye tracking device

- A specific clock display has been developed in order to be visible on videos during the recording. This is necessary in order to match data between the driving simulator videos and the eye tracker device. The clock displays time with milliseconds precision and is not visible by participants during the experiment. Figure 99 shows the display of the clock.

Figure 99: Clock display during video recording

- As the LMA driving simulator is a fixed base simulator, brake profile deceleration was adjusted to fit a more realistic brake profile due to the lack of physical sensation. The brake deceleration profile is given in Figure 100.

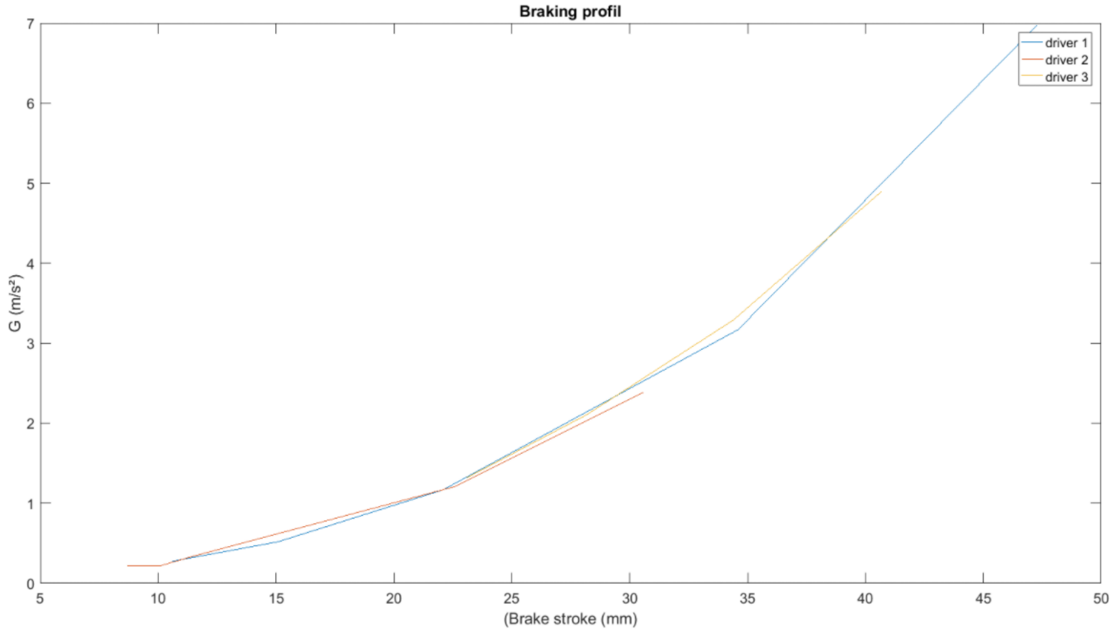


Figure 100: Brake deceleration profile of the driving simulator

3.3 Scenario description

3.3.1 Which scenario to reproduce and how?

In order to design the different scenarios for the driving simulator study, it is necessary to determine what will be integrated inside each scenario. Thus, it requires analyzing the elements that can intervene in the accident like the infrastructure, the visibility criteria, how and when to trigger the VRU, the theoretical approach speed of the car, the VRU displacement speed and so on. To do so, a visual sketch of each accident cases is required to extract the scenario characteristics. A Matlab script has been written to make a visual representation for each PCM accident cases based on the available data. A visual analysis has been performed on the accident sketches and allowed the extraction of the characteristics described in Table 12. The values found in Table 12 are values that can be found for each scenario. The Table 13 indicates additional values that can be found for some specific scenarios (Longitudinal or Turning scenarios). Some cases were more detailed than others and sometimes the information cannot be known precisely which explains why an “unknown” value has been considered. Last but not least, VRU and car approach speed have also been extracted from the databases. Car approach speed corresponds to the speed prior any braking manoeuver before the impact.

Variable	Description	Values
Origin of the VRU	Indicates where is located the VRU at the beginning of the scenario. It can take 2 additional values in the case of Turning scenarios.	Right / Left Same way / Front (additional values for Turning scenarios)
Number of lanes in the same direction as the car	Indicates how many lanes in the same of the car direction	1 to 4 / Unknown
Total lanes number of the road	Indicates the total lanes number in the same and opposite way	1 to 8 / Unknown
Bicycle path	Indicates if there is a bicycle path and its position relative to the car	Left / Right / Left and Right / Front / No bicycle path
Bus lane	Indicates if there is a bus lane and its position relative to the car	Left / Right / Left and Right / No bus lane
Intersection	Indicates if the case happened at an intersection	Yes / No
Parking space	Indicates the presence or not of a parking space and its location relative to the car	Left / Right / Left and Right / No parking space
Tramway lane	Indicates the presence of tramway lane and its location relative to the car	Left / Right / Left and Right / Center / Front / No tramway lane
Oriented traffic lane	Indicates if there is specific road mark direction (lane directional arrow)	Yes / No
Occlusion	Indicates if an element of the surrounding environment hides the VRU during the accident	Yes / No
Occlusion time	In the case of occlusion, it indicates when the occlusion happened	From TTC 5 to 2.5s / From 2.5s to 0s / Both
Object type	In the case of occlusion, it indicates the type of element that hides the VRU	Car / Bus / Building / Tree or pole / Unknown
Number of objects	In the case of occlusion, it indicates the object number responsible of occlusion	1 to 6

Table 12: General characteristics extracted from accident visual analysis

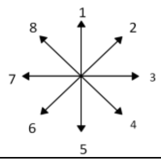
Variable	Description	Values	Scenario where the value is considered
The VRU is swerving	Indicates if the VRU was swerving prior the collision	Yes / No	Longitudinal
Manoeuver of the VRU	Indicates where the VRU is heading	1 to 8 	Turning
Number of lanes in the same way in exit way	Indicates the number of lanes in the way to exit the intersection	1 to 4 / Unknown	Turning
Total number of lanes in the exit way	Indicates the total number of lanes in the way to exit the intersection	1 to 8 / Unknown	Turning
Directional road mark arrow to turn	Indicates if there is a directional road mark arrow to indicate turning lane	Yes / No	Turning

Table 13: Additional characteristics extracted for Longitudinal and Turning scenarios

The characteristic extraction results for each cyclist and pedestrian scenarios in chapter 2 are given in Table 14 and Table 15. It gives indications to recreate accident circumstances for the driving simulator study.

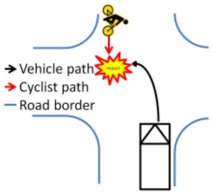
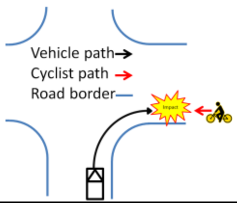
Scenario	C-CN	C-CF	C-L	C-TL	C-TR
Origin	Coming from the right	Coming from the left	On the right side of the road	In front of the car	Coming from the right
Road	2 ways, 1 for each direction	2 ways, 1 for each direction	2 ways, 1 for each direction	- Entering the intersection: 2 ways road, 1 for each direction - Exit: 2 ways, 1 for each direction	- Entering the intersection: 2 ways road, 1 for each direction - Exit: 2 ways, 1 for each direction
Bicycle path	No	No	No	No	No
Bus lane	No	No	No	No	No
At an intersection	Yes	Yes	No	-	-
Parking space	No	No	No	-	-
Tramway lane	No	No	No	No	No
Occlusion	Yes - From TTC 5 to 2.5s for FCW test - 1 object occlusion (not a car, a bus, a tree or pole)	No	No	No	No
Cyclist speed	12-13 km/h	12-13 km/h	14 km/h	14 km/h	13-14 km/h
Car speed	12 km/h	11-12 km/h	28 km/h	17-18 km/h	14-15 km/h
Complementary information			Cyclist is not swerving	- No directional road mark arrow - Cyclist going towards the car 	- No directional road mark arrow - Cyclist going to the left 

Table 14: Results of the characteristic extraction for each cyclist scenario

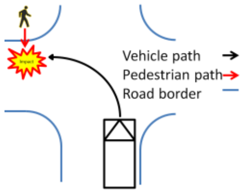
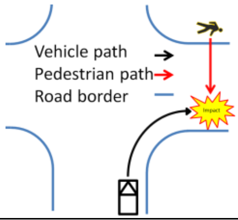
Scenario	P-CN	P-CF	P-L	P-TL	P-TR
Origin	Coming from the right	Coming from the left	On the right side of the road	Located on the left	Located on the right
Road	2 ways, 1 for each direction	2 ways, 1 for each direction	2 ways, 1 for each direction	- Entering the intersection: 2 ways road, 1 for each direction - Exit: 2 ways, 1 for each direction	- Entering the intersection: 2 ways road, 1 for each direction - Exit: 2 ways, 1 for each direction
Bicycle path	No	No	No	No	No
Bus lane	No	No	No	No	No
At an intersection	No	No	No	-	-
Parking space	No	No	No	-	-
Tramway lane	No	No	No	No	No
Occlusion	Yes - From TTC 5 to 2.5s for FCW test - 1 car	No	No	No	No
Pedestrian speed	5 km/h	5 km/h	5 km/h	5 km/h	5 km/h
Car speed	25-30 km/h	30-35 km/h	36-37 km/h	19 km/h	16 km/h
Complementary information			Pedestrian is not swerving	- Pedestrian is going towards the car 	- Pedestrian is going towards the car 

Table 15: Results of the characteristic extraction for each pedestrian scenario

In Euro NCAP test protocol, different crossing test scenarios have been considered since a few years. Thus, due to the limited number of participants for the driving simulator study, it has been decided to focus insufficient explored scenarios like pedestrian and cyclist turning scenarios. Pedestrian and cyclist longitudinal scenarios are also considered for FCW analysis based on Euro NCAP test protocol for AEB. Next section describes more in detail the progress of the chosen scenarios.

3.3.2 Familiarization scenario

This scenario aims to familiarize participants with the virtual environment and the driving controls of the simulator. Participants drive in an urban environment close to real conditions with different traffic situations without pressure on the driver. The mean duration of this scenario is about 13 minutes. During the driving, participants experiment different distraction tasks and FCW triggers. Participants realize 4 distraction tasks, 2 audio-cognitive and 2 visual fairly distributed along the driving. Distraction tasks and the FCW signal are described in more detailed in next sections. Participants also experiment

2 FCW triggers during the driving, once for a real positive trigger and once for a false positive trigger. The true positive is triggered due to a pedestrian crossing the road in front of participant's car at about 4 minutes after the beginning of the scenario. The pedestrian is visible far in advance and remains static until the crossing action is triggered. The pedestrian crosses the road on a zebra crossing. The FCW signal is triggered 2s before impact with the pedestrian. The false positive is triggered in a straight road with no traffic on opposite lane, no traffic in front of participant's car and with no VRU close to the road. The false positive signal is triggered at about 8 minutes after the beginning of the scenario. The true positive trigger is used to be the first-time experience of the system. The false positive trigger is used in order to avoid an automatic reaction to the FCW system.

3.3.3 Pedestrian Longitudinal (P-L)

The Pedestrian Longitudinal configuration is as follow: a pedestrian walks along the pavement on the right side of the road in the same direction as participant's vehicle. Initially hidden by a parked vehicle on the pavement, the pedestrian goes down on the road at 0.8m far from the side of the pavement and then walks along on the road. There is traffic on opposite lane and the pedestrian walks at a speed of 1.5m/s. The configuration is set up when the pedestrian is at 0.8m from the side of the pavement. To create accident circumstance, participants are asked to realize a visual distraction task to not allow them to see the pedestrian's shifting on the road. This can avoid anticipation or premature driver's reaction. The configuration is shown in Figure 101 and Figure 102. During the whole scenario, 2 visual secondary tasks are triggered on straight road including the one at the critical situation. A FCW system can be triggered 2s or 1.7s before the impact or not depending to the test condition. The mean duration for this scenario is between 5 to 10 minutes.

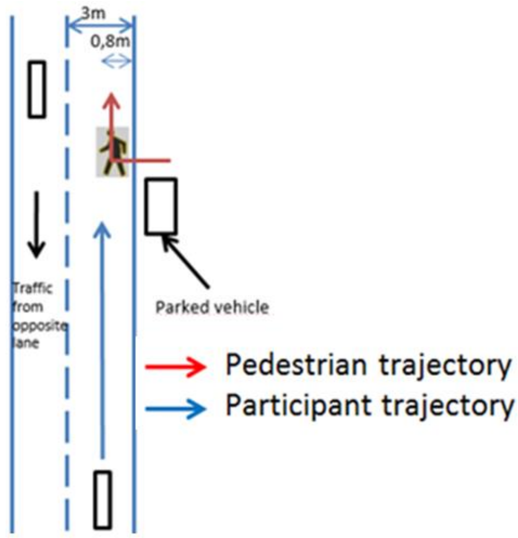


Figure 101: Pedestrian Longitudinal configuration

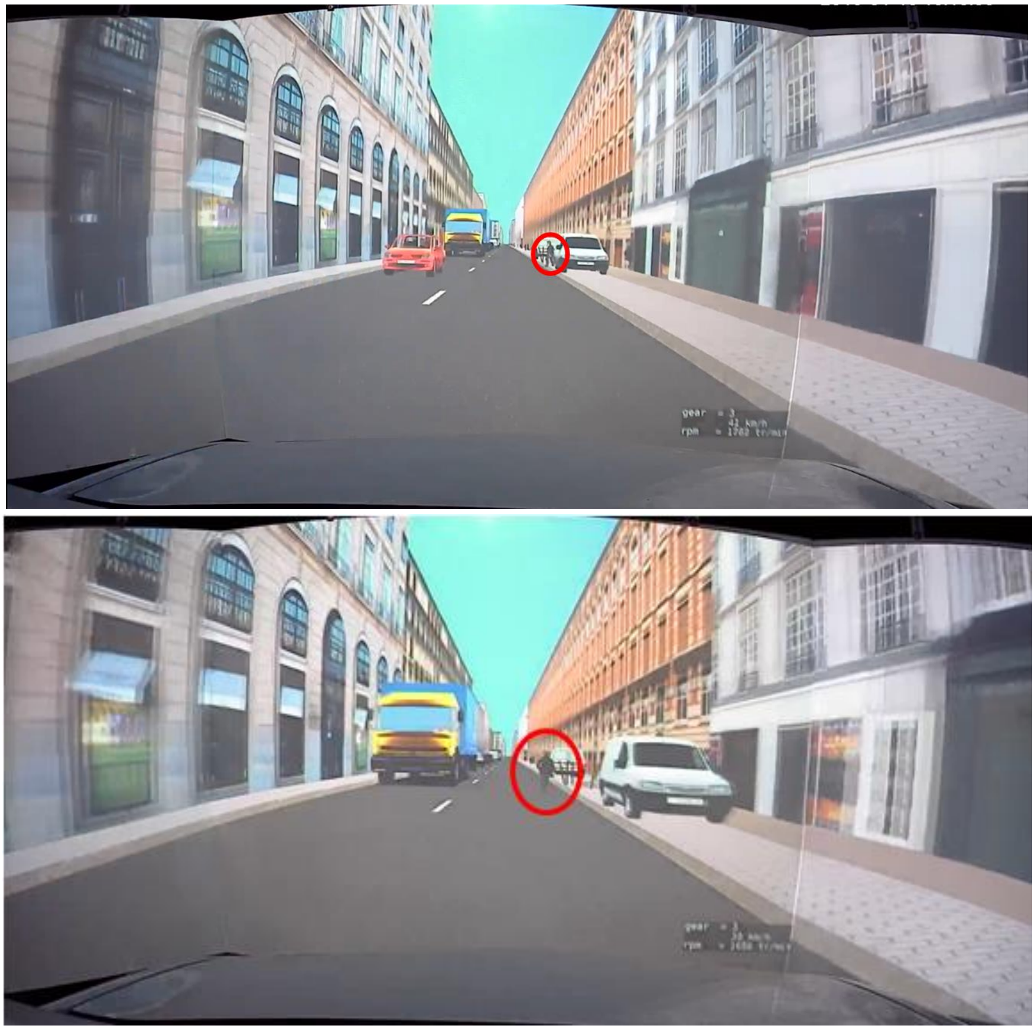


Figure 102: View of the pedestrian set-up (beginning and end) for the P-L scenario

3.3.4 Cyclist Longitudinal (C-L)

The Cyclist Longitudinal configuration is as follow: a cyclist rides along the pavement on the right side of the road in the same way as participant's vehicle. There is traffic on opposite lane and the cyclist rides at a speed of 5m/s. Initially, the cyclist rides on the pavement. When the participant's vehicle approaches, the cyclist shifts at 0.8m from the pavement to the right side of the road. Similarly to the Pedestrian Longitudinal scenario, participants are asked to realize a visual secondary task to create accident circumstance. It can also avoid participants to see the cyclist' shifting. Figure 103 and Figure 104 show the Cyclist Longitudinal configuration. During the whole scenario, participants experiment 2 visual secondary task triggers on straight line including the one at the critical situation. A FCW system can be triggered 2s or 1.7s or not before the impact depending to the test condition. The mean duration for this scenario is between 5 to 10 minutes.

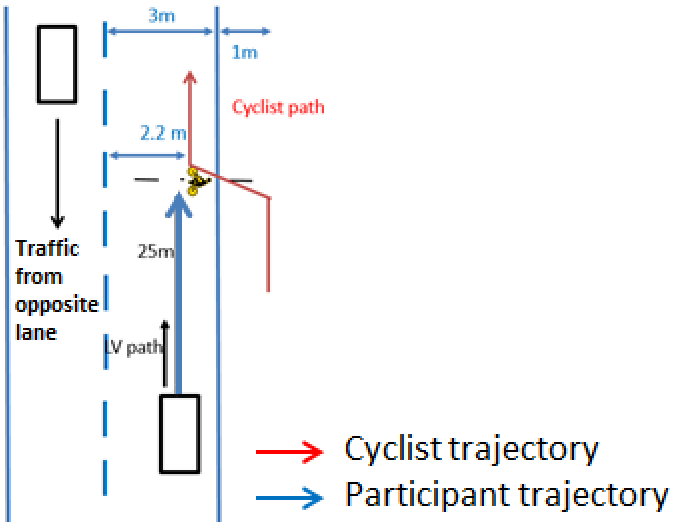


Figure 103: Cyclist Longitudinal configuration

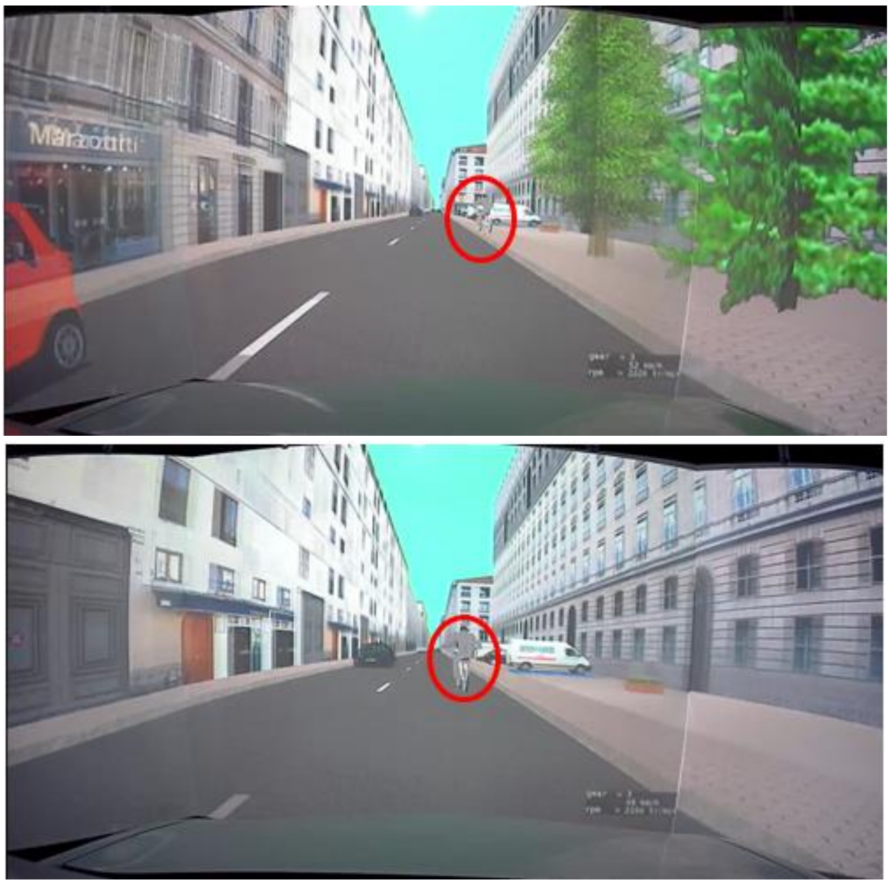


Figure 104: View of the cyclist set-up (beginning and end) for the C-L scenario

3.3.5 Turning Left and Pedestrian Left (TL-PL)

The configuration of this scenario is as follow: participants are asked to turn left at a crossroad and a pedestrian crosses the road on the left side of the road. There is no dynamic traffic during this configuration and the pedestrian crosses the road at a speed of 1.5m/s. To create accident circumstances, participants are asked to realize an audio-cognitive task. Figure 105 and Figure 106 show the Turning Left and Pedestrian Left configuration. During the whole scenario, participants experiment 2 audio-cognitive tasks including the one at the critical situation. The mean duration for this scenario is between 5 to 10 minutes.

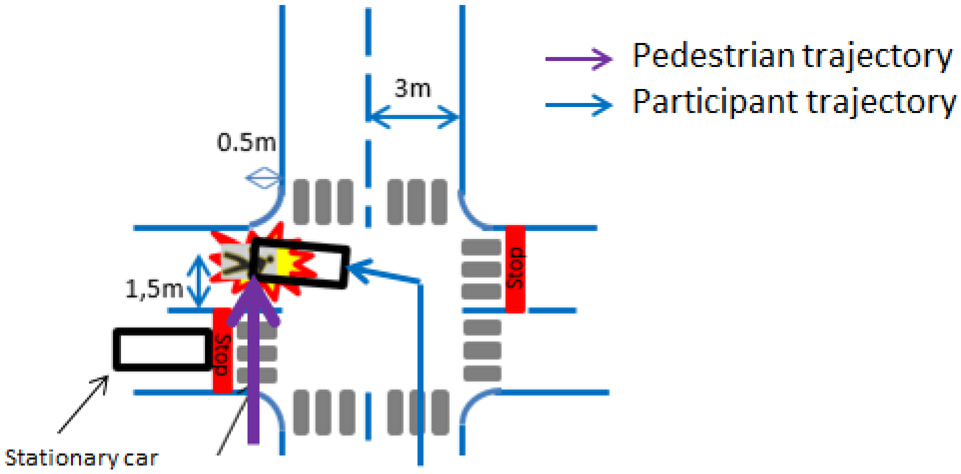


Figure 105: Turning Left and Pedestrian Left configuration

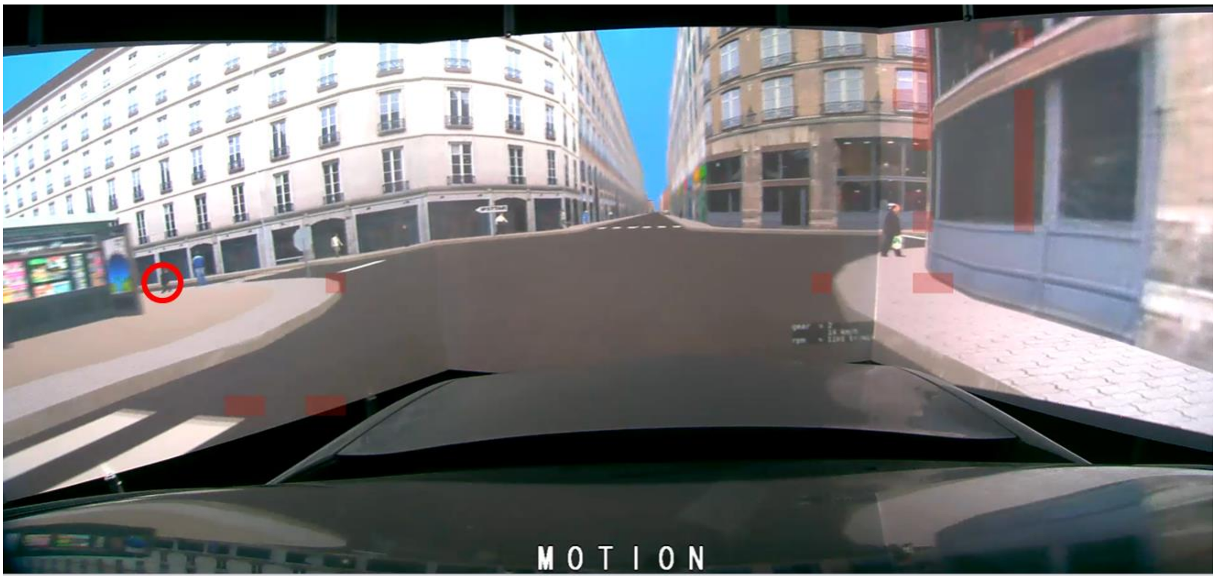


Figure 106: View of the TL-PL scenario

3.3.6 Turning Left and Pedestrian Right (TL-PR)

The configuration of this scenario is as follow: participants are asked to turn left at a crossroad and a pedestrian crosses the road on the right side of the road. There is no dynamic traffic during this configuration and the pedestrian walks at a speed of 1.5m/s. Similarly, to TL-PL, participants are asked to realize an audio-cognitive task. Figure 107 and Figure 108 show the Turning Left and Pedestrian Right configuration. During the whole scenario, participants experiment 2 audio-cognitive tasks including the one at the critical situation. The mean duration for this scenario is between 5 to 10 minutes.

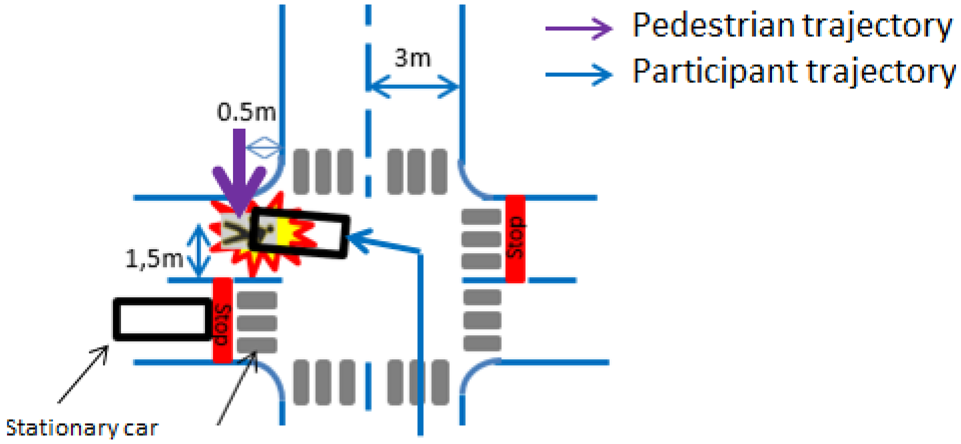


Figure 107: Turning Left Pedestrian Right configuration

Figure 108: View of the TL-PR scenario

3.3.7 Turning Right and Pedestrian Right (TR-PR)

The configuration for this scenario is as follow: participants are asked to turn to the right at a crossroad and a pedestrian crosses the road on the right side of the road. There is no traffic during this configuration and the pedestrian walks at a speed of 1.5m/s.

During this configuration, participants are asked to realize an audio-cognitive task. Figure 109 and Figure 110 show the Turning Right and Pedestrian Right configuration. During the whole scenario, participants experiment 2 audio-cognitive tasks including the one at the critical situation. The mean duration for this scenario is between 5 to 10 minutes.

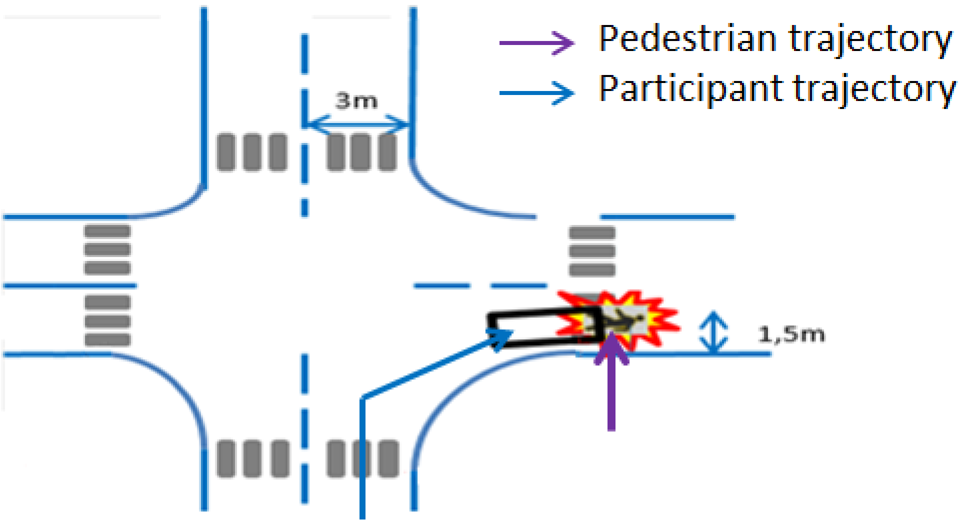


Figure 109: Turning Right and Pedestrian Right configuration

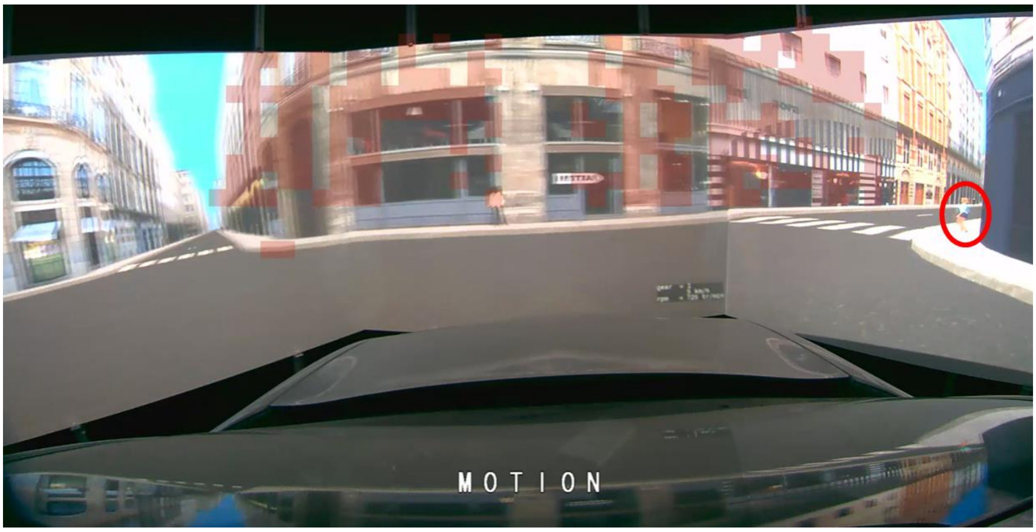


Figure 110: View of the TR-PR scenario

3.3.8 Turning Left and Cyclist Right (TL-CR)

The configuration for this scenario is as follow: participants are asked to turn to the left at a crossroad and a cyclist is coming on the opposite lane on the road. When approaching this crossroad and after having followed a bus, there is no dynamic traffic during this configuration. Only a stopped bus is located on the left road at a stop road mark. The cyclist is coming on the opposite line at a distance of 0.3m to the side of the pavement and rides at a speed of 5m/s. During this configuration, participants are asked to realize an audio-cognitive task. Figure 111 and Figure 112 show the Turning Left Cyclist Right configuration. During the whole scenario, participants experiment 2 audio-cognitive tasks including the one at the critical situation. The mean duration for this scenario is between 5 to 10 minutes.

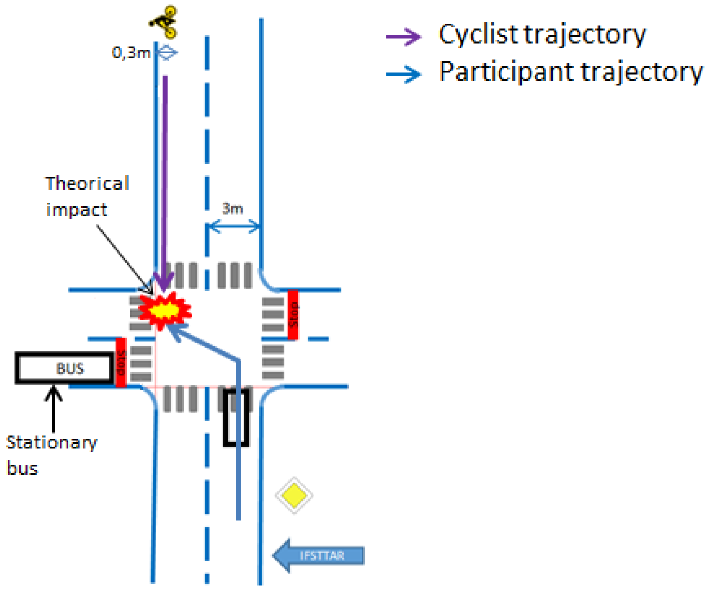


Figure 111: Turning Left Cyclist Right configuration

Figure 112: View of the TL-CR scenario

3.4 Secondary tasks

The conclusion of preliminary trials for the reproduction of accident scenarios revealed that no accident occurs in normal driving condition (e.g. when drivers are focused on the driving task). Thus the introduction of a secondary task is intent to increase the accident occurrence for the considered scenarios. The distraction task should allow reproducing the driver's behaviour during the accidents as it occurred in real-life. Ideally, the same distraction task should be used for all scenarios and feasible by all everyone (no specific skill required). A visual-cognitive distraction is required in Longitudinal configuration in order for drivers not to see the set-up of the VRU and prevent premature reaction. However, it is not possible to visually distract drivers during a turning manoeuver. That is why, an audio-cognitive task has been chosen for this kind of scenarios. Nevertheless, audio-cognitive task might not be sufficient to avoid anticipation behaviour.

3.4.1 Secondary visual-cognitive task

Visual distraction in Longitudinal situations is possible as performed by Alonso et al. (2012). In their paper, they used two different tasks to distract drivers: one visual and one cognitive. The cognitive task is a three digit number counting backwards by three in which drivers had to respond every 2s at a beep sound. The visual task is SuRT (Surrogate Reference Task) which also requires a manual interaction as participant uses button to give the answer. The visual task proposed by Alonso et al. (2012) cannot be used here as the FCW has an audio warning interfering with the beep sound that gives the rhythm for driver to answer to the task. The SuRT task is not used here due to the manual interaction that is not suitable in turning scenarios.

In order to visually distract drivers during Longitudinal scenarios, the visual-cognitive task used is closed to the one that can be found in Forkenbrock et al. (2011). Their task starts 5.5s and ends 1.06s before the impact with a stopped car and can be resumed in Figure 113. Our visual secondary task sequence is inspired from them and has been adjusted to fit our scenarios.

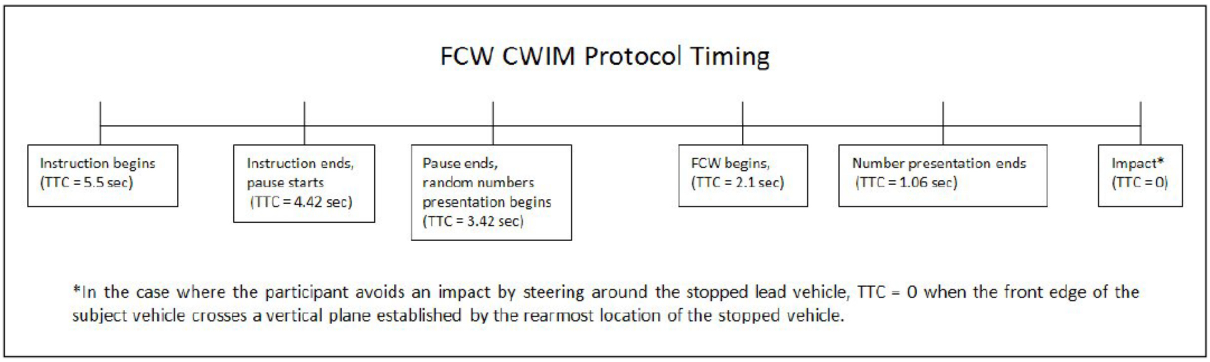


Figure 113: Forkenbrock et al. (2011) distraction task sequence

The visual task is a task that requires participant's visual attention. To do so, driver has to look at a small screen located inside the car, similarly at a place where an on-board computer can be found. When the task begins, an audio message warns the driver of the beginning of visual task through the message “visual task” (“tâche visuelle” in French). 1.5s later the screen inside the car lights up and displays the message “tâche visuelle” for 0.5s. Then 5 digits are displayed continuously every 0.5s. Finally, after having shown the 5th digit during 0.5s, the screen turns off and the driver has to repeat the 5 digits in their appearance order. The driver answers while still driving. After the screen turns off the impact should occur 0.6s later without reaction of the driver at constant speed. Figure 114 shows the progress of the visual secondary task that is launched just before a longitudinal critical situation. This type of visual task is only used for Longitudinal scenarios as it is not possible to visually divert drivers’ attention during a turning manoeuver. Visual tasks are also used twice during the familiarization scenario in order for drivers to get acquainted with this task while driving. Additionally, a training with a minimum of 3 trials is performed during the briefing without driving to be sure that the participants have understood the instructions. Participants are asked to give at least one answer after the digit display even if they have not seen any digit or if they do not remember the digit series. Example of possible answers when this case happens can be “I don’t remember”, “I have not seen any digit” or “I don’t know”. This instruction is recalled before the beginning of each Longitudinal scenario.

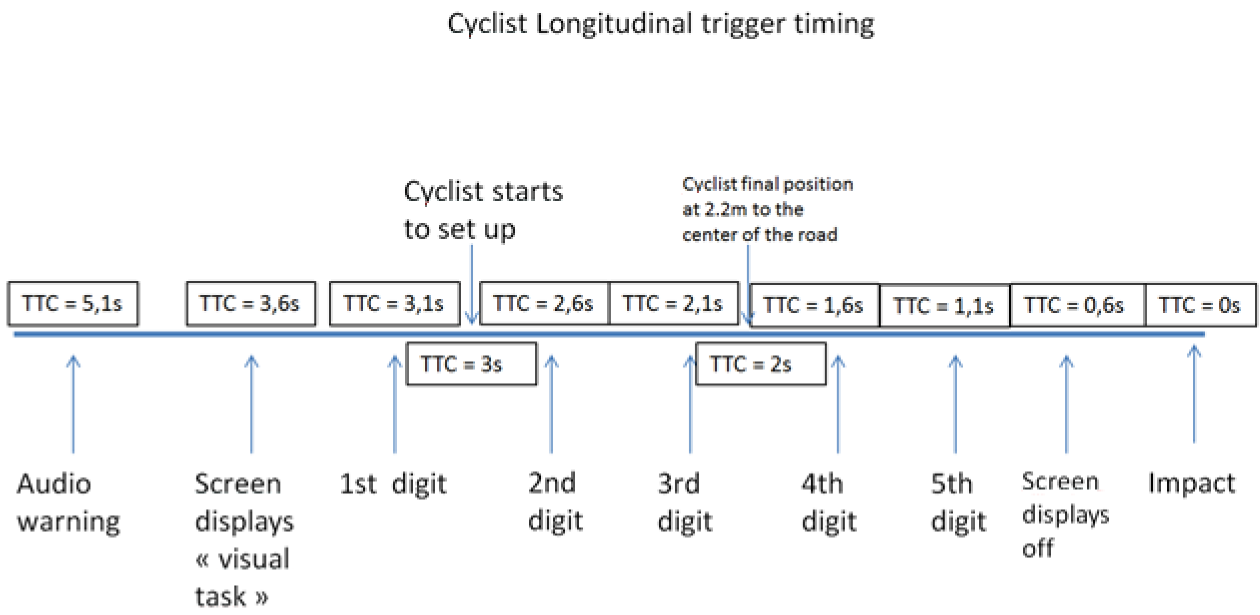


Figure 114: Example of visual task for Cyclist Longitudinal scenario. The progress is the same for Pedestrian Longitudinal

3.4.2 Audio-cognitive task

For Turning scenarios, our task is a combination of Mehler et al. (2011) and Turner and Engle (1989). Mehler et al. (2011) proposed an n-back task. This task consists of repeating a sequence of digit with a shift corresponding to the *n* number. The digits are given every

2.25s. Turner and Engle (1989) used arithmetic operation composed of two arithmetic operations (multiplication or division and addition or subtraction). In our task, we replace the two arithmetic operations by a combination of single digit multiplication and memorisation operation.

The chosen audio-cognitive task is a task that requires drivers' audio and mental attention. To do so, drivers have to listen a record that gives a series of random digits one by one and give answers during the progress of the record. The record begins with an audio message that warns drivers of the beginning of this task through the message "secondary task" ("tâche secondaire" in French). Then every 2.25s a digit is given. Participants are asked to give the results of the multiplication of the 2 previous digits during the record progress. Figure 115 shows the progress of this task with the answer participants have to give in red. Time To Collision (TTC) is the time prior the theoretical impact.

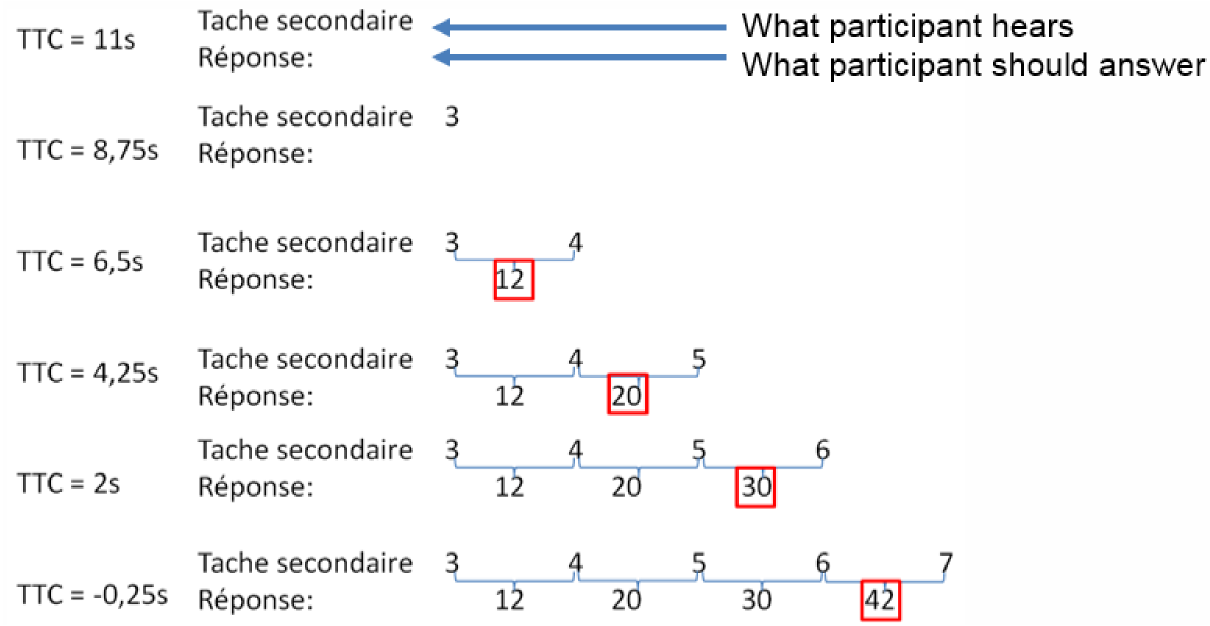


Figure 115: Audio-cognitive task and participant's answer progress

At TTC = 11s, the task start warning "tâche secondaire" is given

At TTC = 8.75s, the 1st digit is given

At TTC = 6.5s, the 2nd digit is given, the participant has to answer 12 (=3*4) and remembers the digit 4 for the next calculus.

At TTC = 4.25s, the 3rd digit is given, the participant has to answer 20 (=4*5) and remembers the digit 5 for the next calculus.

At TTC = 2s, the 4th digit is given, the participant has to answer 30 (=5*6) and remembers the digit 6 for the last calculus.

At TTC = -0.25s (0.25s after the theoretical impact), the participant has to answer 42 (=6*7).

Audio-cognitive tasks are used only for Turning scenarios where it is not possible to visually divert drivers' attention. Audio-cognitive tasks are also used twice during the familiarization scenario in order for participants to get acquainted with this task while driving. Additionally, a training with a minimum of 3 trials is performed during the briefing without driving to be sure of the instruction correct understanding. Participants are asked to give at least one answer during the task record even if they do not know the correct answer to the calculus. When this case happens, example of possible answers can be "I pass" or "I don't know". This instruction is recalled before the beginning of each Turning scenario.

3.5 FCW signal

FCW trigger is an alarm composed of an audio and a visual signal. The audio FCW specification is shown in the Figure 116. It consists of a repeated beep for a total duration of 2 seconds. The visual signal is a message displayed on the driving simulator central screen with the content "brake" ("freinez" in French). This message is visible through the windshield in its lower part as shown in Figure 117.

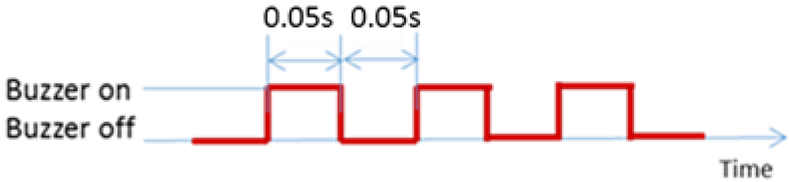


Figure 116: Audio FCW specification

Figure 117: Visual display of FCW signal on the simulator screen and from passenger seat point of view

Two values have been considered in this study about the FCW trigger time: 1.7s and 2s. The choice of those values is based on the accident analysis results. Most last time to activate the brakes (t_{LTTB}) in order to avoid the collision can be found around 1.5s for pedestrians and 1s for cyclists. By adding the driver reaction time, it can be considered that the potential time to trigger a FCW can start from about 1.5s prior the theoretical impact. A reference for the 1.7s can be found in Euro NCAP test protocol (Euro NCAP 2017a). Comparing the FCW effects depending on the two trigger times appears to be interesting either on the drivers' reaction time or on their acceptance afterwards.

Different elements are considered for the triggering of the FCW. Among them, we find the current speed and the trajectory of both the car and the VRU. In order to trigger a warning, the first thing to consider is the impact location. Its location is located in the center of the way of the involved vehicle in this study. The impact location depends on the trajectories of the VRU and the car. For the car, the travelled distance is estimated depending on the scenario. When driving in a straight line the calculation of the travelled distance is simple as it corresponds to a line segment. In the case of a turning scenario, a curve that can correspond to a quadrant is used to estimate the travelled distance. This estimation appears to be an appropriate mean estimation between drivers who cut the bend and the others who can turn too large. With the trajectory established as mentioned previously, it is then possible to determine the time to reach the impact location. This calculus is based on the distance to the impact location and the instant speed of the vehicle assuming the vehicle will continue with constant speed. This assumption is false as during a turning manoeuver, the vehicle speed decreases at the beginning of the turning and then increases (Wolfermann et al. 2011). However, as it is not possible to predict all possible trajectories and speed profile, the trigger of the FCW has been based on the car mean constant travelling speed hypothesis. With this hypothesis and knowing the instant speed of the car, it is possible to compute and trigger the FCW at the wanted timing 1.7 or 2s prior the theoretical impact. Prior the triggering of FCW, the VRU is already in motion.

3.6 Data collection

3.6.1 Driving simulator file

After a participant's run, a driving simulator file containing data is collected. The file contains the time, participant's vehicle positions, instant speeds, pedal depressions (gas and brake pedal), VRU's positions, VRU's instant speeds and markers to indicate specific interest elements like FCW signal trigger, VRU movement trigger or secondary task beginning. With those data, it is possible to extract if the participant has hit the VRU and thus then the total collision number, the time to release the gas pedal, the time to trigger the brakes. The method to get each of those results is described below:

- The number of accidents
  This variable indicates the number of collision if the participant hits the VRU during the driving scenario. It is possible to determine if there is a collision from participant's car and VRU positions. For each couple position (car and VRU), a specific bounding box surrounding each position is considered to determine if they intersect at any time. The dimension of the bounding boxes is taken from Euro NCAP test protocol (Euro NCAP 2017b).
- The time release the gas pedal
  Gas release pedal is a good indicator of drivers' physical reaction. To obtain this value, the theoretical impact time is first calculated. When approaching the hazard situation in the scenario, the VRU is triggered at a specific moment based on the participant's time to collision. As it is not possible to know in advance the participant's reaction, an estimation of this time to collision has been set based on driver's instant speed. From this estimation, it is possible afterwards to get the theoretical impact time. Then, we search the first peak or the last stable value back in time from the theoretical impact time. Finally, the subtraction between the theoretical impact time and the time of peak of last stable value gives the gas release time. The reason is that it reflects the decision to quickly release the pedal in emergency situation. The calculated time is a negative value as it is the time before the TTC. During the analysis, it has been decided to limit the reaction to less than 4s before the theoretical impact as reaction prior this time cannot be considered as a sudden emergency reaction. This is indicated with "<-Xs" (where X is an integer value higher than 4) in the raw data chart. Figure 118 illustrates an example of value extraction. On this figure, the red circle highlights the peak indicating the sudden release of the gas pedal.

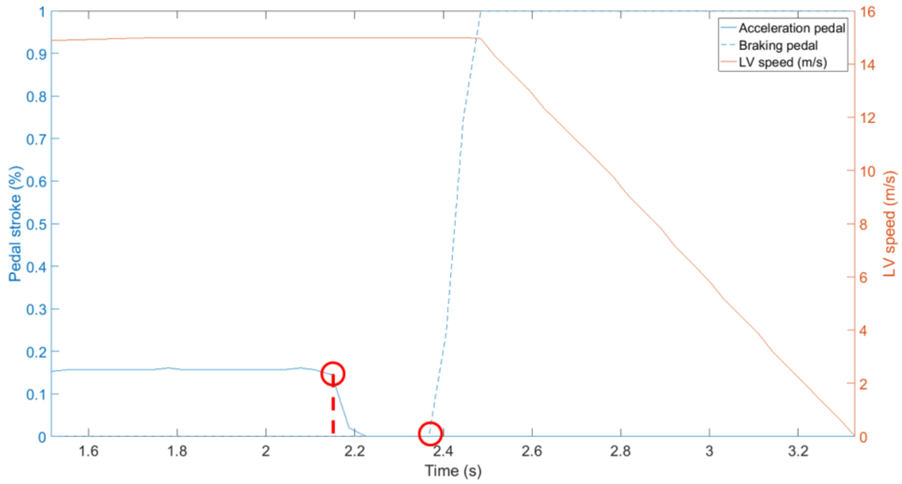


Figure 118: Gas and brake pedal time extraction

- The time to trigger the brakes
  Similarly to the gas pedal release, the brake pedal trigger is obtained after determining the theoretical impact time. We search back in time the first non-zero value corresponding to the brake pedal. The subtraction of the theoretical impact time and the first non-zero value corresponds to the brake pedal trigger. This value is negative as it is the time before the TTC. During the analysis, it has been decided to limit the reaction to less than 4s before the theoretical impact. This is indicated with "<-Xs" (where X is an integer value higher than 4) in the raw data chart. The red circle on Figure 118 also illustrates the extraction of the braking triggering time.
- The driver reaction to a FCW signal
  For participants who experienced scenarios with a FCW trigger, it is possible to extract driver reaction times. Here two values will be computed; the mean duration to begin releasing the gas pedal from the FCW signal and the mean duration to start depressing the brake pedal from the FCW signal. The calculus consists of subtracting to the FCW trigger time the time where the gas pedal is released or the brake is depressed. Only participants who have released the gas pedal after the FCW signal and have depressed the brake pedal before the theoretical impact have been considered in the calculus of those two durations. With it, it is possible to compute a driver reaction interval from the mean value plus or minus the standard deviation.

3.6.2 Driving simulator video files

As previously described, video files of participants' run are recorded. Four different videos are collected (Figure 99). The top left video corresponds to a camera placed on the roof of the car. It records the surrounding driving environment in front of the driver with a larger angle. This video is useful in situation requiring a large field of view like in turning scenarios where the gaze can be lost by the eye tracker device. The top right video corresponds to the environment in front of driver from his/her point of view with the clock displayed for gaze analysis. The bottom left video shows the foot on different pedals of the car. The bottom right video records participants' face. It allows the monitoring during the driving to ensure no simulator sickness, to control gaze direction when the secondary task is triggered and help understanding driver's behavior during the scenario. Those four cameras are complementary and are of great help in the comprehension and understanding of driver's reaction.

3.6.3 Facelab eye tracker result files

The eye tracker device gives different result files which contain the time, gaze X and Y positions and if the gaze is located on the pre-defined area. This pre-defined area corresponds to the driving simulator screens in front of the driver. A combination of the driving simulator file and Facelab eye tracker file leads to a final video in which the gaze behavior can be extracted and analyzed to better understand drivers' visual behavior. This gaze location video is also used in order to define if the participant realizes the visual-cognitive task in Longitudinal scenario. Three principal values are defined with an additional one when data are missing.

- 'Yes' if participant realized the task completely or was focused on it until the trigger of FCW without glance back to the road during the task.
- 'No' if participant was not focused on the secondary task. It corresponds to participants who looked continuously to the road and saw the VRU during the set-up or to participants who refuse to realize the task after its trigger in order to stay focus on the road.
- 'Partially' value is given when participant focused partially on the secondary task and on the road.
- 'Undefined' value is given when a technical issue or record failure occurs even if participant's answer has been obtained. In this case, as the timeline of the event is not known, the effect of the secondary task cannot be determined and so is classified as "undefined".

Videos are realized using Matlab® scripts (Matlab 2012) and required the Matlab Image Processing Toolbox. The general algorithm to make the video is given here.

The video of the screen where the gaze will be added is collected (video with a clock display). This video is converted into a sequence of frames. For each frame, the time is extracted from the clock display and converts to Unix Time Stamp. A correspondence is realized to match each eye tracker data to each of the previously frames. Transformations (translation and rescale) are performed on gaze coordinates and the results of the transformation are added on the final frames as a marker. Finally, all frames with the gaze location are converted into a video. Figure 119 summarizes the whole process.

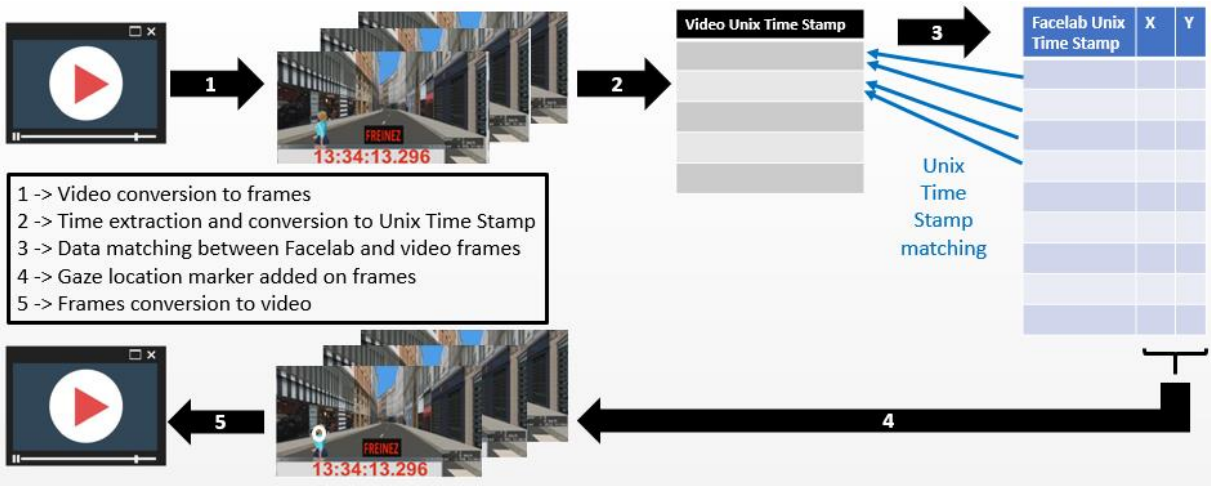


Figure 119: Algorithm for creating videos with gaze location

3.6.4 Audio record

An additional camera has been placed inside the car in order to record participants' answer to the secondary task. It allows determining if the secondary task is done partially, totally or not for the audio-cognitive task. It also helps a better comprehension of participant's reaction. The camera is placed on the passenger seat and does not affect the checking of the car right mirror.

3.6.5 Questionnaires and interviews

Participants fill a questionnaire in order to gather general data about them (see Annex B). Information relative to their age, gender and driving habit have been collected. Participants also have to fill in two Karolinska Sleepiness Scale tests (Kaida et al. 2006) which indicate their awareness at the beginning of the experiment and at the end. An interview is realized just after the end of the driving session in order to collect participants' feedbacks about each scenario and the FCW signal. This interview is useful in order to collect the drivers' perception of the driving situation: the course of the driving scenario, the perception or not of the FCW and their reaction to it. Their feeling about the signal is also gathered with their general feedback about the experimented FCW signal. Their feedbacks are divided into 3 distinct parts. One concerns the FCW audio signal, one the FCW visual signal and the last one the FCW trigger timing. This part concerns only people who have experimented a FCW trigger during their 3 driving scenarios. The questionnaire can be found in Annex B. Data relative to the questionnaire have been collected but most of them have not been processed. Only the data relative to drivers' reaction and feedbacks about the FCW system have been processed. Further work can consider the analysis of the remaining data.

3.7 Experimental management

3.7.1 Ethical approval

Prior to the experiment an ethic committee has been consulted. This committee's role is to warn staff, increase their awareness and answers the ethical questions relative to experimentations. A detailed document is given to the committee describing the context, the contents of the current experimentation with a description of the different scenarios, data collection, procedure of gaze data acquisition, a description of the secondary task used during the experiment, the sample size, the experimental session duration per participant and the results exploitation method (see Annex C). The document also contains a notice with some mandatory legal information and the consent form that will be given to all participants. After review of the document and update if needed, an agreement is given for the experimentation in July the 20th 2017.

3.7.2 Protocol

All participants have the same experiment protocol for a maximum expected duration of 2 hours. After the welcome, participants read a short notice about the experiment. They fill a consent form and also some questionnaires. They give general information about them and fill a first Karolinska Sleepiness Scale. They set their driving position inside the car and are told to keep it until the end of the experiment. Then there is a step of eye tracker device calibration for gaze analysis. Next, explanations about FCW functioning is given with demo of the audio and visual signal. Also, a training is performed on the visual and audio-cognitive tasks with a minimum of 3 trials for each. Thus those 3 trials allow checking the correct instructions understanding by the participant. The training is performed without driving. Next the driving part starts on 3 different scenarios with a break between each scenario. All participants experiment the familiarization scenario at their first try. For the second and third scenario, two scenarios are chosen between the 6 scenarios presented in section 3.4. Finally, a second Karolinska Sleepiness Scale is filled and an interview is realized to get participants' feedback on their driving session and on the FCW device. Participants do not experiment two Longitudinal or two Turning scenarios when it is possible. Participants also experiment 2 scenarios with the same condition, i.e. they experiment 2 scenarios without a FCW trigger or with a 2s FCW trigger or a 1.7s FCW trigger. The order of the scenario is also randomized and counterbalanced. If one participant experiments a Longitudinal and a Turning scenario, another participant experiments the same scenarios but with the order reversed.

Instructions are given to participants at the beginning of each scenario. Participants are instructed to follow the predetermined way at maximum authorized speed when possible. They are also instructed to change gear and to drive as naturally as possible. The maximum authorized speed is 50kph. Participants are informed of the presence of a speed limiter that prevents them from driving faster than 53kph. They are also informed of the different tasks they can encountered (visual and/or audio-cognitive) during the driving with a recall of the corresponding instructions. They are told that they can encounter visual and audio-cognitive task in the case of the familiarization scenario, only an audio-cognitive task for a Turning scenario or only a visual task for a Longitudinal scenario. The task instructions are recalled before each scenario. Naturally, participants are not informed of the nature of the scenario they experiment. The total duration for one participant can be decomposed as indicated in Table 16.

Experiment phase	**Estimated duration**
Welcome and briefing	10 min
Fill forms and questionnaires	10 min
Eye tracker calibration	10 min
FCW explanation and secondary task trainings	10 min
Familiarization scenario	13 min
Break	10 min
Scenario 1	10 min
Break	10 min
Scenario 2	10 min
Questionnaires, interviews, debriefing and rest	30 min
Total	120 min

Table 16: Experimental session for each participant

3.7.3 Participant sample and data matrix

180 people have been recruited for this experiment. All participants are middle-aged drivers from 25 to 55 years old. They also have at least 3 years of driving experience and are non-professional drivers. They were spread into 3 different conditions: without FCW trigger, with FCW trigger 2s or 1.7s before the theoretical impact. As each participant experiments 2 scenarios, a total of **360** data can be collected. Table 17 shows the ideal expected data matrix prior the beginning of the experimentation.

Scenario / Condition	Without FCW	With FCW 2s	With FCW 1.7s	Total
TR-PR	20	20	20	60
TL-CR	20	20	20	60
TL-PL	20	20	20	60
TL-PR	20	20	20	60
P-L	20	20	20	60
C-L	20	20	20	60
Total	120	120	120	360

Table 17: Planned data matrix

Unfortunately, some participants have simulator sickness and the total number of exploitable data is lower than **360**.

A total of **69** data are excluded here due to simulator sickness or technical issue. Additionally, some of the participants have experienced scenarios with difference compared to the main experiment group. Thus **37** data are also excluded from the results presented in this section. They correspond to 18 data from participants who have experienced a TL-CR and a TL-PL scenario and to 19 data from participants who have experienced a C-L scenario. Those 18 first data were participants who have experienced TL-CR and TR-PR scenarios without secondary task. Indeed, during the first runs, the objective was to determine if a secondary task was required in order to reproduce accident during a turning manoeuver. As no accident was observed during both scenarios, it was concluded that turning scenarios require a secondary task. More surprisingly, recreating a TL-CR scenario is more complex as expected as all drivers declare that they did not perform emergency manoeuver and consider the TL-CR driving situation as not difficult to handle. With this result for TL-CR scenario, it has been decided to perform additional adjustments on this scenario as described later in the section 3.9. Concerning the 19 data for C-L scenario, it corresponds to tests for the secondary task trigger and instructions given to participants prior the scenario. The trigger timing has to be considered carefully in order to avoid participants to see the set-up of the cyclist and then react prematurely. On the other hand, the task should not end to early based on the theoretical impact otherwise there might be no collision with the cyclist even for the without FCW modality. Additionally, it is difficult to divert visually drivers for a long duration even when driving on a straight road. The final task trigger is as described in section 3.4. Concerning the instructions, telling participants that they must realize the secondary task completely is challenging. Such an instruction might be convenient as it helps recreate the C-L scenario with a collision. However, the task might bypass the FCW signal resulting in no effect. The compromise finally results in an instruction asking participants to give an answer at the end of the task as described in the secondary task section.

37 participants have been kept for the additional experiment resulting in 74 data not included into the results described in this section but in the additional experiment section.

To summarize, among the 360 expected data, 74 data (37 participants) are kept for the additional experiment, 69 data correspond to simulator sickness and not usable and 37 correspond to data performed on different conditions. It leaves us with a final total of 180 data for this main study as shown in Table 18.

Scenario / Condition	Without FCW	With FCW 2s	With FCW 1.7s	Total
TR-PR	14	16	17	47
TL-CR	10	-	-	10
TL-PL	14	-	-	14
TL-PR	19	15	-	34
P-L	15	18	-	33
C-L	10	16	16	42
Total	82	65	33	180

Table 18: Actual data distribution for each scenario and each condition

3.8 Results

Each of the next section gives the previously described results for each scenario modality without or with FCW trigger and a comparison between the FCW trigger modalities. Raw results can be found in Annex D.

3.8.1 Pedestrian Longitudinal (P-L)

The Table 19 below summarizes the results without and with FCW for this scenario. Participants who have not fully released the gas pedal or have not trigger the brakes are not considered in the calculus of the mean value.

For the without FCW modality, 8 data are not considered: 4 for the gas release and 4 for the brake activation.

For the FCW 2s modality, 5 data are not considered: 2 for the gas release and 3 for the brake activation.

Those not considered data are participants who have reacted too early (more than 4s before the theoretical impact).

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	3	-1.700	0.782	-1.699	0.356	- 3 fully distracted - 8 partially - 4 not distracted	15
FCW 2s	7	-1.865	0.542	-1.605	0.332	- 5 fully distracted - 7 partially - 4 not distracted - 2 unknown	18

* SD = standard deviation

Table 19: Results data for P-L scenario

Values presented in Table 20 are only estimations of the potential driver reaction time. It is hypothesized that the driver reaction is due to the FCW which may not be currently the case. Even with the help of the interview, determining if the driver reaction is really caused by the FCW appears to be difficult. Participants who have released the gas pedal and have braked before the collision have been considered in the results presented below. It corresponds to only 5 participants. Thus, results have to be considered with caution as the dispersion can be important and due to the sample size.

	FCW 2s	
	Gas release duration (s)	Brake trigger duration (s)
Mean	0.3802	0.8014
Standard deviation	0.4323	0.4042
Upper limit	0.8125	1.2056
Lower limit	-0.0521*	0.3971

*This negative value is due to the calculus formula of the lower value

Table 20: Driver reaction times for P-L scenario with a FCW 2s

Comparison between without FCW and FCW 2s

- Number of accidents

Without FCW, there are 3 accidents out of 15, which represent 20% accidents on this modality. With FCW 2s, there are 7 accidents out of 18 which represent 39%. There are nearly twice more accidents when a FCW is triggered on this scenario.

Participants without FCW who struck the pedestrian were fully distracted and none of them braked. Additionally, one of them did not fully release the gas pedal.

Among participants with FCW who struck the pedestrian: 4 were fully distracted until FCW triggering with 2 of them who did not braked at all, two others were partially distracted and the last one is undefined for the secondary task realization. The undefined participant had not brake and had not fully released the gas pedal.

When fully distracted, it appears that the current scenario settings do not leave time for participant to react to avoid the impact. For partially distracted participants, whether or not there is an accident depends directly on when the participants looked back to the road during the task prior the impact. Among all the partially distracted participants, those two who collided with the pedestrian were on the FCW group. The higher accident rate on the FCW 2s group may be then due to the sample. The final participant classified as undefined had similar results to those fully distracted and may be considered in that group.

- Gas pedal release time

An ANOVA test has been performed only on participants who have released the gas pedal less than 4 seconds before the theoretical impact. The result of the ANOVA test shows that hypothesis H0 (mean values with and without FCW are equal) is not rejected,

$F(1,25) = 4.24$; $p = 0.62$. Figure 120 shows the boxplot for each group without or with FCW 2s trigger.

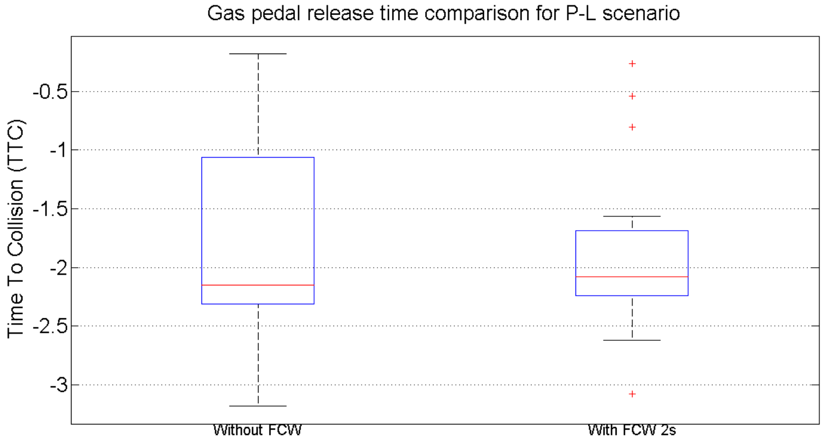


Figure 120: Gas pedal release boxplot for P-L scenario

- Brake trigger time

An ANOVA test has been performed only on participants who have depressed the brake pedal less than 4 seconds before the theoretical impact. The result of the ANOVA test shows that hypothesis H0 (mean value with and without FCW are equal) is not rejected, $F(1,24) = 4.26$; $p = 0.63$. Figure 121 shows the boxplot for each group without or with FCW 2s trigger.

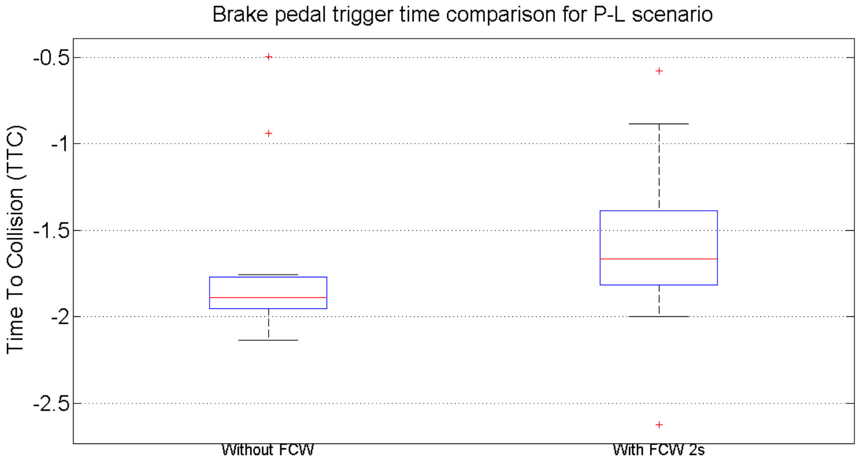


Figure 121: Brake pedal trigger boxplot for P-L scenario

- Distraction level analysis

An additional analysis is performed on the data based on participants' distraction level with the help of gaze analysis.

An ANOVA test is made based on the distraction level for scenario with FCW 2s and without FCW. Results show that for a distraction level, there is no statistical difference with or without FCW.

Mean reaction values for gas pedal release and brakes trigger are given in the Table 21 below for each distraction level. Some mean braking values are earlier compared to mean gas release values. This effect can be observed because of the data considered in the calculus of the mean value. Indeed, reaction values more than 4s before the theoretical impact have not been included in the calculus. However, one value close to that limit has been kept as it was below the 4s threshold, leading to a shifting of the final mean value.

	No FCW		**FCW 2s**	
	Mean gas release pedal (s)	Mean brakes trigger (s)	Mean gas release pedal (s)	Mean brakes trigger (s)
Distracted drivers	-0.621	-0.496	-1.373	-1.670*
Partially distracted drivers	-1.66	-1.71*	-2.107	-1.504
Not distracted drivers	-2.29	-1.98	-2.093	-1.725

* The mean braking value is earlier compared to the mean gas release value because of 1 very early reaction.

Table 21: Mean reaction values for different distraction level for the P-L scenario

It can be noticed that the not distracted participants react earlier than partially distracted participants who react earlier than distracted participants for the without FCW modality. This phenomenon is visible both for the time to release the gas pedal and for the time to depress the brakes. A statistical difference is observed for the time to depress brakes depending on the distraction level only for the no FCW modality. On contrary, no statistical difference can be observed for the gas release time and the brake trigger for the FCW 2s modality based on the distraction level. Also, no statistical difference can be observed for the gas release time for the no FCW modality.

Conclusion for P-L

The proportion of collision without and with FCW warning is low. The simulated configuration seems to be easy to manage by most participants. Indeed, for most participants, it appears that the pedestrian is well-identified even if participants are asked to realize a distraction task. For distracted drivers, nearly all drivers collide with the pedestrian even with a FCW triggered 2 seconds prior the theoretical impact. These results are in line with Bueno et al. (2014) findings. They showed that attentional resources are required to process the warning. Additionally, Harbluk et al. (2007) showed that visual behavior and braking performances are affected by distraction task. Thus, the more drivers are involved in a distraction task, the less effective a warning can be. This indicates that FCW could not avoid collision but suggests potential mitigation possibility. For non-distracted drivers, their reaction time to brake is more than 2s before the expected impact. So the FCW seems to have low effect on this situation. Nevertheless, it can be considered that the simulated situation was not complex enough to reproduce accident without FCW. This can be due for different reasons: the driving speed instruction have not been followed, the pedestrian appears too early or the distraction task is not attractive enough. On those drivers, the FCW triggering might possibly have adverse effect. Indeed, triggering a warning signal if the driver considers managing correctly the situation might be disturbing and then reduces the effectiveness of a braking for example. Thus, the system trigger conditions and timing need to be chosen carefully.

Concerning the proportion of simulated collision, even if the accident rate is higher in the FCW 2s group compared to the without, the higher rate may be caused by the participant sample. The results highlight that a visual distraction is required in order to recreate accident circumstances. However, it appears difficult to distract drivers long enough to set-up the pedestrian into accident configuration.

Concerning reaction time, no statistical differences can be observed either for the time to release the gas pedal or for the time to depress the brakes considering our entire sample. There are also twice more accidents with a FCW 2s compared to the no FCW modality. This might be due to the participant sample and will require further works and investigations. Differences can be observed only based on drivers' distraction level, the more distracted the later they react. For non-distracted drivers, they tend to react in about 1s after having identifying a potential hazard represented by the pedestrian with the braking activation.

3.8.2 Cyclist Longitudinal (C-L)

The Table 22 below summarizes the results of the three modalities for this scenario. Participants who have not fully released the gas pedal or have not trigger the brakes are not considered in the calculus of the mean value as participants who react too early (more than 4s prior the theoretical impact).

For the without FCW modality, 3 data are not considered: 2 for the gas release and 1 for the brake activation.

For the FCW 2s modality, 1 data is not considered: 1 for the gas release.

For the FCW 1.7s modality, 3 data are not considered: 2 for the gas release and 1 for the brake activation.

Those not considered data are participants who have reacted too early (more than 4s before the theoretical impact).

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	2(1)	-1.958	0.629	-1.747	0.478	- 1 fully distracted - 3 partially - 6 not distracted	10
FCW 2s	1	-2.134	0.519	-1.633	0.549	- 5 fully distracted - 4 partially - 7 not distracted	16
FCW 1.7s	3	-1.982	0.586	-1.635	0.466	- 4 fully distracted - 7 partially - 5 not distracted	16

* SD = standard deviation

(1) One impact not with the cyclist but with the oncoming traffic

Table 22: Results data for C-L scenario

As for P-L, values presented in Table 23 are estimations of the potential driver reaction time. It is based on only 5 participants with the FCW 2s modality and to 3 participants with the FCW 1.7s modality. Results have to be considered with caution as the dispersion can be important and due to the sample size.

	FCW 2s		FCW 1.7s	
	Gas release duration (s)	Brake trigger duration (s)	Gas release duration (s)	Brake trigger duration (s)
Mean	0.6248	1.1774	0.8373	1.2447
Standard deviation	0.3653	0.4986	0.4033	0.4272
Upper limit	0.9901	1.6760	1.2406	1.6718
Lower limit	0.2595	0.6788	0.4341	0.8175

Table 23: Driver reaction times for C-L with a FCW 2s and FCW 1.7s

Comparison between without FCW, FCW 2s and FCW 1.7s

- Number of accidents

Without FCW, 2 accidents out of 10 happen, which represents 20% on this modality. With a FCW 2s trigger, this rate reaches 1 out of 16 with a rate of 6.25%. With FCW 1.7s, there are 3 accidents out of 16 which represent 18.75%.

All participants who had an accident were distracted except for one on the without FCW group who was partially distracted and had an accident not with the cyclist but with the oncoming traffic. It can be assumed that fully distracted drivers will lead to a collision similarly to the P-L scenario. However, some fully distracted participants avoided the impact (4 on the FCW 2s group and 1 on the FCW 1.7s). Two reasons can explain that result. Three participants (2 on the FCW 2s and 1 on the FCW 1.7s group) depress the brake pedal more than 1s prior the impact. The speed reduction of the vehicle combined with the cyclist also going forward gives some additional time for the car to reach the cyclist. This additional time gives enough time for the cyclist to go further and then be out of reach of the car allowing collision avoidance. For the two remaining participants of the FCW 2s group, it appears that they depressed the brake pedal very close to the theoretical impact time (less than 1s prior the impact). However, they avoided the collision not thanks to their braking but due to their position on the road. With consideration of car and cyclist bounding boxes, there is still enough space for the vehicle to drive next to the cyclist even if that space is small. If the cyclist was in the very front of the vehicle, then those participants would have hit the cyclist. Thus, the accident avoidance is not caused by the FCW.

- Gas pedal release time

An ANOVA test has been performed. Figure 122 shows the boxplot for each group without FCW or with FCW 2s or 1.7s. The result of the ANOVA test shows that hypothesis H0 (mean value with and without FCW are equal) is not rejected, **$F(2,34) = 3.28$; $p = 0.80$**.

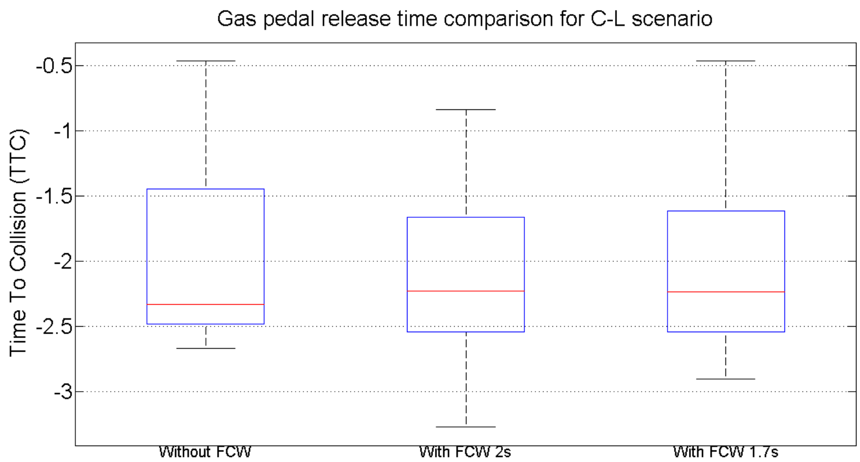


Figure 122: Gas pedal release boxplot for C-L scenario

- Brake trigger time

An ANOVA test has been performed. Figure 123 shows the boxplot for each group without FCW or with FCW 2s or 1.7s. The results of the ANOVA test shows that hypothesis H0 (mean value with and without FCW are equal) is not rejected, **$F(2,37) = 3.25$; $p = 0.89$**.

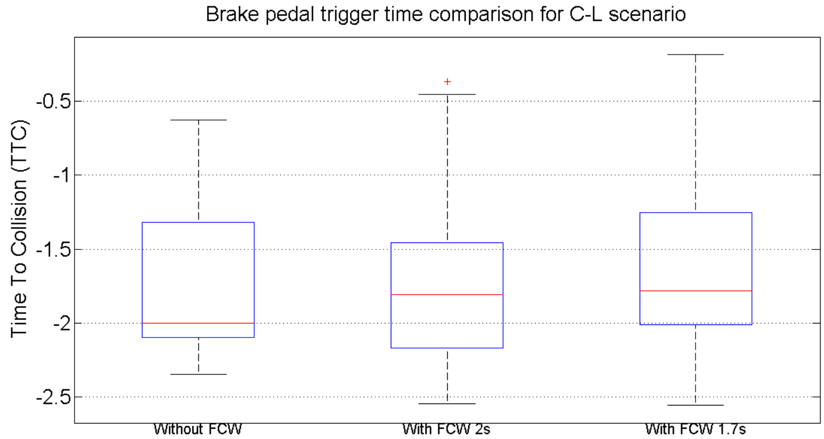


Figure 123: Brake trigger time boxplot for C-L scenario

- Distraction level analysis

An additional analysis is performed on the data based on participants' distraction level with the help of the gaze analysis. Similarly to P-L scenario, mean reaction to release gas pedal and to trigger brakes are earlier for not distracted participants than partially distracted and distracted. This trend can be observed for all modality without FCW, with FCW 2s and with FCW 1.7s for each three distraction levels. Mean reaction values are shown is the Table 24 below.

	No FCW		FCW 2s		FCW 1.7s	
	Gas release (s)	Brake trigger (s)	Gas release (s)	Brake trigger (s)	Gas release (s)	Brake trigger (s)
Distracted	-0.461	0[1]	-1.41	-0.80	-0.99	-0.76
Partially distracted	-1.45	-1.03	-2.07	-1.70	-2.15	-1.64
Not distracted	-2.46	-2.11	-2.68	-2.19	-2.61	-2.16

[1] Only 1 participant is fully distracted without FCW. This participant did not brake.

Table 24: Mean reaction time for different distraction level

Conclusion for C-L

The proportion of collision with and without FCW warning is low. This simulated configuration seems to be easy to manage by most participants. In a similar way than P-L scenario, the cyclist is well-identified even with the presence of a distraction task. Non-distracted participants early braking reactions more than 2 seconds prior the theoretical impact indicate that the FCW will have low effect for this configuration for attentive drivers. Collision with the cyclist can be find only among fully distracted participants indicating that this element is necessary to lead to accident. As mentioned previous for P-L scenario, the distraction task can affect the effectiveness of a warning. Due to the task, attentional resources might not be available affecting then the visual behavior and potentially the braking performances. However, as the results show it, not all distracted drivers hit the cyclist. Many reasons can explain it: the cyclist can be seen too early or the cyclist displacement speed. Indeed, cyclist higher speed compared to pedestrian allows to increase avoidance possibility even with a later driver's reaction. This is why contrary to P-L scenario, there are less collision among fully distracted participants. Nevertheless, it can be observed faster reaction time among distracted drivers thanks to FCW trigger. Additionally, it can be also highlighted that potential reaction induced by FCW is similar whatever the FCW trigger timing (Table 23). This result indicates potential positive effect of FCW. So it could be interesting to distinguish the difference between this positive effect due to FCW and the higher cyclist speed still allowing avoidance without the help of FCW. Potential driver's reaction results from Table 23 support values chosen during chapter 4 for FCW benefit estimations with braking reaction ranging from 0.6s to 1.7s.

The proportion of collision with the cyclist is low even without FCW trigger revealing that reproducing this accident configuration is still complex and difficult. Further investigation is required in order to reproduce this scenario in a driving simulator with higher collision rate. However, results of the current settings indicate that when the visual distraction is able to visually divert eyes off the road and long enough in time, a collision with the cyclist can be reproduced.

Concerning the reaction time, no statistical difference can be observed considering all data from our sample for the time to release the gas pedal and the time to depress the brakes.

Similarly to P-L scenario, the more distracted are the drivers, the later they react. A statistical difference can be observed only based on the distraction level.

For non-distracted drivers, it appears that they react faster compared to P-L scenario with brake activation in less than 1s.

3.8.3 Turning Left Pedestrian Left (TL-PL)

The Table 25 below summarizes the results for the scenario without FCW only. Participants who have not fully released the gas pedal or have not trigger the brakes are not considered in the calculus of the mean value as participants who react too early (more than 4s prior the theoretical impact).

For the without FCW modality, 1 data is not considered for the gas release.

The boxplots for the gas release time and the brake activation are shown in Figure 124 and Figure 125.

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	0	-2.529	0.572	-1.915	0.537	- 14 fully distracted	14

* SD = standard deviation

Table 25: Results data for the TL-PL scenario

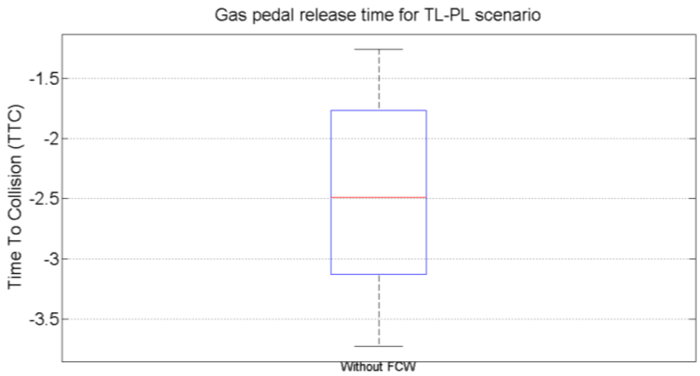


Figure 124: Gas pedal release time for TL-PL scenario

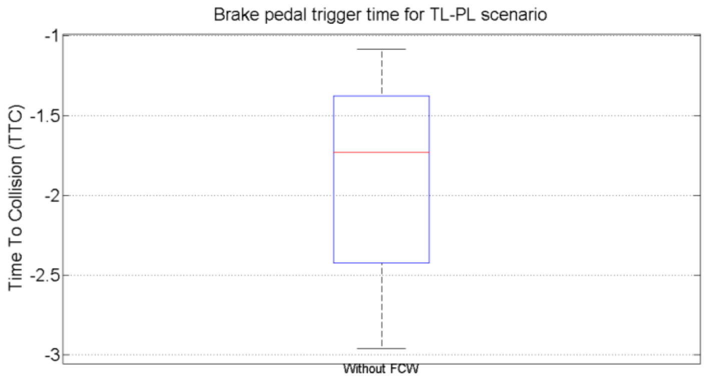


Figure 125: Boxplot of the brake trigger time for TL-PL scenario

Conclusion for TL-PL

No accident is observed without FCW and the situation appeared too easy to manage by the volunteers. Indeed, speed reduction to realize a turning manoeuver combined with the possibility to see the pedestrian very early have led to no collision. Results indicate that drivers have reacted very early more than 2s prior the theoretical impact suggesting that FCW could have little or no effect for this situation. An additional experiment has been realized in order to verify this result with modified settings.

3.8.4 Turning Left Pedestrian Right (TL-PR)

The Table 26 below summarizes the results of the two modalities for this scenario. Participants who have not fully released the gas pedal or have not triggered the brakes are not considered in the calculus of the mean value as participants who react too early (more than 4s prior the theoretical impact).

For the without FCW modality, 2 data are not considered for the gas release.

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	2	-1.797	0.403	-1.247	0.212	- 19 fully distracted	19
FCW 2s	3	-1.847	0.415	-1.171	0.180	- 14 fully distracted - 1 partially	15

* SD = standard deviation

Table 26: Results data for TL-PR scenario

Values presented in Table 27 are only estimations of the potential driver reaction time. Nine participants have been considered in the results because they have released the gas pedal and have braked before the collision.

	FCW 2s	
	Gas release duration (s)	Brake trigger duration (s)
Mean	0.477	0.878
Standard deviation	0.2776	0.2238
Upper limit	0.7546	1.1018
Lower limit	0.1993	0.6542

Table 27: Driver reaction times for TL-PR with a FCW 2s

Comparison between without FCW and with FCW 2s

- Number of accidents

Without FCW there are 2 accidents out of 19 which correspond to an accident rate of 10.5%. With a FCW 2s trigger, 3 out of 15 people have an accident which represents 20%. The low collision rate in the without FCW group indicates that the current audio-cognitive distraction is not sufficient enough to lead to a collision or that the scenario is not critical enough. Further investigations are required in order to increase the collision rate in this scenario. Additionally, speed profile analysis may be of help to distinguish behavior that can lead to a collision.

- Gas release time

An ANOVA tests is performed on those data. The results of the ANOVA test reveals that we do not reject hypothesis H0 (mean value with and without FCW are equal), **F(1,30) = 4.17; p = 0.76**. Figure 126 shows the boxplot for gas release time for TL-PR scenario.

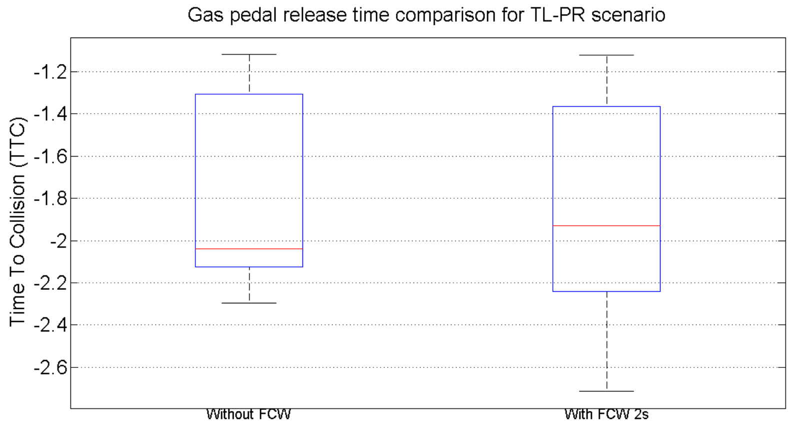


Figure 126: Gas release time boxplot for TL-PR scenario

- Brake trigger time

An ANOVA test has been performed on those data. The results of the ANOVA test reveals that the HO hypothesis (mean value with and without FCW are equal) is not rejected, **F(1,32) = 4.15; p = 0.38**. Figure 127 shows the boxplot of those two samples.

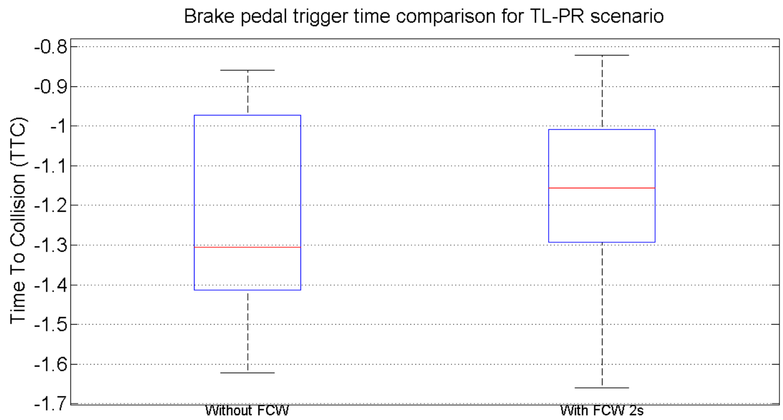


Figure 127: Brake trigger time boxplot for TL-PR scenario

Conclusion for TL-PR

The proportion of collision with and without FCW warning is low for this scenario. The simulated configuration seems to be easy to manage for most participants. Indeed, only a few collisions is observed even with a distraction task. This might support the idea that drivers still have sufficient attentional resources to react properly without FCW help. Driver's reaction appears to be similar with and without FCW suggesting potential low effect of FCW for this configuration. Possible reason supporting this idea could be speed reduction during the turning manoeuver rendering the avoidance less difficult. It could also come from the possibility to perceive the pedestrian in central vision as the pedestrian is located close to the front of the car when turning. Nevertheless, results of potential driver's reaction to a FCW from Table 27 support values chosen during chapter 4 for FCW benefit estimations with values ranging from 0.6s to 1.1s.

No statistical difference can be observed during this scenario either for the time to release the gas pedal or the time to depress the brake pedal. Drivers tend to release the gas pedal close to 2s prior a theoretical impact and brake more than 1s.

It can be concluded that the current scenario setting is not critical enough. The audio-cognitive task is not sufficient enough to lead to high collision proportion.

3.8.5 Turning Right Pedestrian Right (TR-PR)

The Table 28 below summarizes the results of the three modalities for this scenario. Participants who have not fully released the gas pedal or have not trigger the brakes are not considered in the calculus of the mean value as participants who react too early (more than 4s prior the theoretical impact).

For the without FCW modality, 2 data are not considered: 1 for the gas release and 1 for the brake activation.

For the FCW 2s modality, 3 data are not considered: 2 for the gas release and 1 for the brake activation.

For the FCW 1.7s modality, 2 data are not considered: 1 for the gas release and 1 for the brake activation.

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	1	-1.298	0.360	-0.848	0.188	- 13 fully distracted - 1 unknown	14
FCW 2s	0	-1.657	0.430	-0.993	0.136	- 16 fully distracted	16
FCW 1.7s	2	-1.166	0.132	-0.844	0.152	- 17 fully distracted	17

* SD = standard deviation

Table 28: Results data for the TR-PR scenario

Table 29 are estimations of the potential driver reaction time. Twelve participants have been considered for the FCW 2s modality and 16 participants for the FCW 1.7s modality.

	FCW 2s		FCW 1.7s	
	Gas release duration (s)	Brake trigger duration (s)	Gas release duration (s)	Brake trigger duration (s)
Mean	0.5703	1.029	0.8339	1.156
Standard deviation	0.1971	0.1419	0.1753	0.1790
Upper limit	0.7673	1.1709	1.0092	1.3350
Lower limit	0.3732	0.8871	0.6586	0.9770

Table 29: Driver reaction times for TR-PR with a FCW 2s and FCW 1.7s

Comparison between without FCW, with FCW 2s and 1.7s

- Number of accidents

Without FCW, there is 1 accident out of 14 participants which represents a rate of 7% With FCW 2s, there is no accident out of 16 participants (0%). With FCW 1.7s, the accident rate reaches 2 out of 17 which represent 12%.

As the collision proportion is low on the without FCW modality, it appears that this scenario is not critical enough. The audio-cognitive task is not sufficient to lead to a collision.

- Gas release time

An ANOVA test has been performed and it appears that the H0 hypothesis (mean values with and without FCW are equal) **is rejected** for at least one group, **$F(2,40) = 3.23$; $p = 0.03$**. Figure 128 shows the boxplot for those three groups.

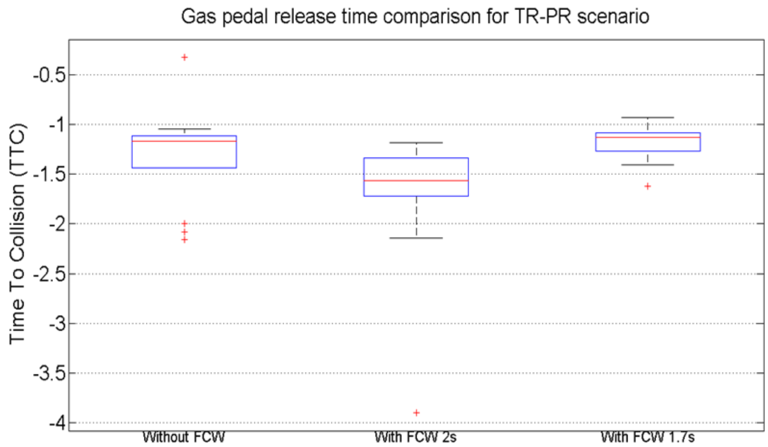


Figure 128: Gas pedal release boxplot for TR-PR scenario

- Brake trigger time

An ANOVA test has been performed on those data and it appears that the H0 hypothesis (mean value with and without FCW are equal) is not rejected **F(2,41) = 3.23; p = 0.14**. Figure 129 shows the boxplot for those three groups.

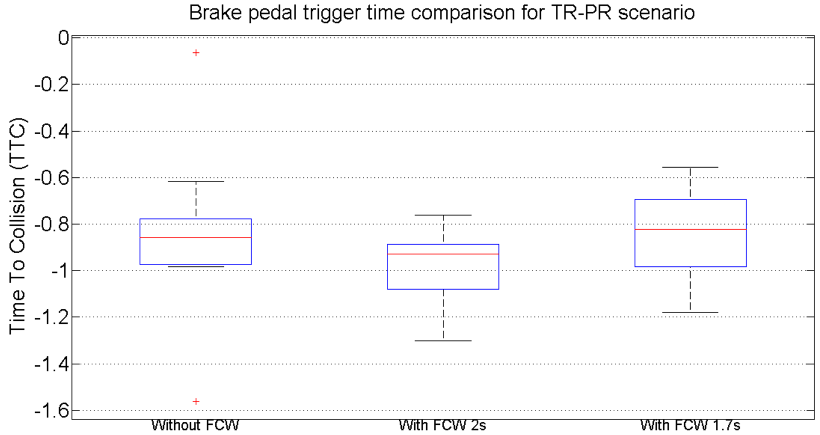


Figure 129: Brake trigger boxplot for TR-PR scenario

Conclusion for TR-PR

Low proportion of collision is observed with and without FCW warning. This simulated configuration seems to be easy to manage by most participants even if this scenario is the most critical configuration. Indeed, the moment when the pedestrian is visible is the shortest compared to the three other turning left scenarios. With drivers starting to react more than 1s prior the theoretical impact, results could suggest that speed reduction during this turning right manoeuver could be sufficient enough to render this current configuration not difficult to manage. Potential braking reaction towards a FCW for this scenario could suggest that the FCW effect is not dependent on the FCW trigger timing. This trend needs to be confirmed. Values from Table 29 support the chosen values used during chapter 4 for benefit estimations with values ranging from 0.8s to 1.4s.

A statistical difference can be observed only concerning the time to release the gas pedal for the FCW 2s group. Even if the gas pedal is released earlier, the time to brake prior the theoretical impact remains similar for all modality. This might be caused by one participant releasing the gas pedal close to 4s prior the theoretical impact. Even without it, drivers with FCW 2s tend to release the gas pedal earlier compared to other modalities.

3.8.6 Turning Left Cyclist Right (TL-CR)

The Table 30 below summarizes the results for this scenario without FCW. No accident occurred during this scenario. For all 10 participants, the current scenario is perceived as not difficult to handle even with an audio-cognitive task during the critical event. Additionally, no behavior can be extracted as there is no emergency reaction.

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	0	NA	-	NA	-	- 7 fully distracted - 3 unknown	10

* SD = standard deviation

NA: not available

Table 30: Results data for the TL-CR scenario

Conclusion for TL-CR

No accident is observed for the without FCW modality. Indeed, the cyclist is visible coming from the opposite lane and participants have declared considering this scenario as a normal driving situation. Without emergency reaction, no results can be extracted from this current scenario. So, this scenario has been modified during an additional experiment in order to provoke emergency reaction and reaction to a FCW.

3.8.7 Participants' feedback on FCW

Participants' feedbacks are collected only for participants who experiment a FCW trigger during a scenario other than the familiarization. They are split in 2 groups, one for each FCW trigger modality (FCW 2s or FCW 1.7s).

Global feedback on FCW audio signal

- For FCW 2s trigger

A total of 42 participants have experienced the FCW trigger 2 seconds prior the theoretical impact. There are 12 positive feedbacks (**28.6%)** for the current audio signal, 15 mitigated remarks or improvement proposal (**35.7%**) and 2 negative ones (**4.8%**). 13 participants (**31%**) have given no opinion on the audio signal. Positive feedbacks indicate no need of modification of the current signal presented in part 3.3. Mitigated remarks correspond to participants who are not totally satisfied of the current beep signal but not unsatisfied either. Sometimes, a suggestion is given like playing the sound louder, or reliability of the system trigger. Negative feedbacks express a preference for another type of signal or people who are not convinced by the current signal.

- For FCW 1.7s trigger

A total of 18 participants have experienced the FCW trigger 1.7s prior the theoretical impact. There are 5 positive feedbacks (**27.7%**), 4 mitigated remarks or improvement proposal (**22.2%**) and 8 negative feedbacks (**44.4%**). Feedback for 1 participant (**5.5%**) is difficult to classify into a positive or negative feedback. Positive feedbacks indicate no need of modification of the current signal. Mitigated feedbacks correspond to improvement needed. Negative feedbacks concern the sound that is not distinctive enough from other sounds that can be encountered inside the car. It can also be a replacement of the audio beep by an audio message like "brake" or "react".

Global feedback on FCW visual signal

- For FCW 2s trigger

A total of 42 participants have experienced the FCW trigger 2 seconds prior the theoretical impact. There are 6 positive feedback (**14.2%**) for the current visual signal, 13 mitigated remarks or improvement proposal (**31.0%**) and 8 negative feedbacks (**19.0%**). There is also 1 neutral feedback (**2.4%**) which find the signal nor useful nor annoying, 12 participants with no opinion (**28.6%**) and 1 participant (**2.4%**) who have not seen the signal due to the presence of eye tracker cameras inside the car. Finally, there is 1 feedback (**2.4%**) that is difficult to classify as a positive or negative feedback. Negative feedbacks express that the message does not attract driver's attention enough and or not perceived on time.

- For FCW 1.7s trigger

A total of 18 participants have experienced the FCW trigger 1.7 seconds prior the theoretical impact. There are 4 positive feedbacks (**22.2%**), 13 mitigated or improvement remarks (**72.2%**), no negative feedback. There is also 1 person without opinion (**5.6%**). Mitigated feedbacks are mostly improvement suggestions.

Global feedbacks on FCW trigger timing

- For FCW 2s trigger

A total of 42 participants have experienced the FCW trigger 2 seconds prior the theoretical impact. There are 8 positive feedbacks (**19.0%**), 2 mitigated feedbacks (**4.8%**) and 17 negative feedbacks (**40.5%**). There are also 12 people without opinion (**28.6%**) and 3 people which find the trigger as late (**7.1%**) but it is not possible to classify their opinion as positive or negative. Positive feedbacks indicate not need to change trigger timing. The mitigated feedbacks are related to trigger that may bring a contribution or not depending on the situation. The negative feedbacks are related to signal trigger which should be earlier.

- For FCW 1.7s trigger

A total of 18 participants have experienced the FCW trigger 1.7 seconds prior the theoretical impact. There are 4 positive feedbacks (**22.2%**), 3 mitigated (**16.7%**) and 10 negative feedbacks (**55.6%**). There is also 1 feedback (**5.6%**) for which an earlier trigger of FCW will be more comfortable. This feedback is difficult to classify as positive or negative. Mitigated feedbacks concern situation where the trigger timing may depends on the situation. Negative feedbacks concern people who want an earlier trigger of the device.

Global feedback conclusion

Audio and visual signal have to be improved even if the current signal appears to be accepted by around 25% of participants. On contrary, the trigger timing receives more negative feedbacks and should trigger earlier according to participants. This perception is higher for participants who experience the FCW 1.7s than those for the FCW 2s. It shows that a FCW should mostly be triggered more than 2 seconds prior a collision.

3.8.8 Main experiment conclusion

- No statistical difference can be observed with or without FCW for all our scenarios except for TR-PR scenario. The difference observed only concerns the time to release the gas pedal and is only valid for FCW 2s trigger. The driving experiment results indicate no benefits from the current audio-visual FCW system and with a trigger 1.7 or 2s prior the theoretical collision.
- On Longitudinal scenarios: a statistical difference can be observed based on drivers' distraction level. The more distracted they are, the later they react.
- Drivers' global feedbacks indicate that the warning message needs improvements either for the visual and the audio delivered signal. A small proportion of the participants are satisfied with the presented audio-visual signal. Participants also have negative opinions about the time to deliver the warning. They report that they prefer an earlier trigger compared to the considered timing in this study.
- TL-CR and TL-PL scenarios need adjustments as no accident occurred. In TL-CR scenario, participants did not find the scenario difficult and did not realize emergency manoeuver. Thus, modifications either on the experiment protocol or on scenario will be required to recreate circumstances that will lead to an accident. Those two scenarios will be further investigated in an additional experiment with adjustments as described in next section.
- Potential driver reaction times have been extracted per scenario. It has to be reminded that those results relay on the hypothesis that driver reactions have been triggered only thanks to the FCW. Table 31 summarizes results when considering all data per FCW trigger time. Reaction time to brake goes from 0,6s to 1,2s to a FCW 2s signal while the reaction time to a FCW 1,7s goes from 0,9s to 1,4s. As a recall, data for the FCW 2s contains 31 data (12 from TR-PR, 9 from TL-PR, 5 from P-L and 5 from C-L) and 19 data for the FCW 1.7s (16 from TR-PR and 3 from C-L). Thus, the result for the FCW 1.7 group is strongly influenced by the data from the TR-PR scenario. Interestingly, results in Table 31 might indicate that drivers take more time with a FCW 1.7s compared to a FCW 2s. The later the warning is given, the longer is the reaction. When facing a critical situation, it might

be difficult to act and take the most appropriate decision. Delaying the warning by 0.3s the FCW warning appears to also increase the driver reaction time up to that amount of time. This result has to be considered with caution as it might come from our participant sample. Further investigations will be required to confirm or deny this trend observed in our current sample.

- For Longitudinal scenarios, if the drivers are visually fully distracted, the collision rate could be high. However, for the C-L scenario, the cyclist high speed can contribute to highly reduce the collision probability indicating that VRU speed can counter the distraction effect. For Turning scenarios, the speed reduction to realize the turning manoeuver combined with the possibility to see the VRU early enough seem to compensate the distraction task that was supposed to lead to a collision. However, it was still possible to estimate potential reaction to a FCW as mentioned in the previous point. Results of those estimated values support the choice of the different values used during the next chapter benefit estimations with values ranging from 0s to 1.2s for the P-L scenario, 0.6s to 1.7s for C-L, 0.6s to 1.1s for TL-PR and 0.8s to 1.4s for TR-PR.
- Reproducing accident scenarios is challenging. Reproducing two out of the three components of an accident (infrastructure and the VRU) is possible. However, the third component (the vehicle represented by driver) is far more complex. Adding a distraction task is not necessarily sufficient to lead to collision with the current scenario designs. It is possible to visually distract drivers when driving straight like in Longitudinal scenarios. However, distracting long enough drivers to recreate the accident scenario for the set-up of the FCW system is difficult. For Turning scenarios, visual distraction is not possible. Adding an audio-cognitive task is possible to distract drivers. However, the current distraction is not sufficient enough to lead to collision. Increasing the difficulty of our current task may be a solution. This may be combined with avoiding anticipation behavior through the sudden appearance of the VRU as tried in the additional experiment. Nevertheless, the current experiment still enables us to learn some lessons.

	All FCW 2s		All FCW 1.7s	
	Gas release duration (s)	Brake trigger duration (s)	Gas release duration (s)	Brake trigger duration (s)
Mean	0.5213	0.9724	0.8345	1.17
Standard deviation	0.3091	0.3100	0.2271	0.2384
Upper limit	0.8304	1.2837	1.0615	1.4084
Lower limit	0.2123	0.6624	0.6074	0.9316

Table 31: Potential driver reactions time to a FCW split according to FCW trigger times

3.9 Additional experiment

3.9.1 New experimental protocol

The previous main experiment reveals that for two scenarios there was no accident with the current settings. Thus, an additional experiment has been performed with protocol modifications and also scenario adjustments. 37 participants experiment a TL-CR and a TL-PL scenario without or with a FCW trigger 2s with new settings. The new scenarios and the new secondary task descriptions are given as the new protocol for the experimental session.

The new scenario configurations are the same as in section 3.3 with little modifications.

The familiarization scenario has no longer FCW trigger at all. It contains 2 new audio-cognitive tasks. Additionally, visual-cognitive secondary tasks have been removed. The scenario contains now only 2 secondary tasks instead of 4.

The final new TL-CR critical situation is similar to the one described in section 3.4.8. However, there are some differences on this new scenario. The cyclist is no more visible at first when approaching the intersection. He suddenly appears 2.2s before the theoretical impact with the same trajectory and the same travel speed as before. Figure 130 is an example of the cyclist appearance. Additionally, participants have to perform 4 audio-cognitive tasks during the scenario instead of 2 including the one during the critical situation as described in section 3.4.2. The task can be triggered not only during turning manoeuver.

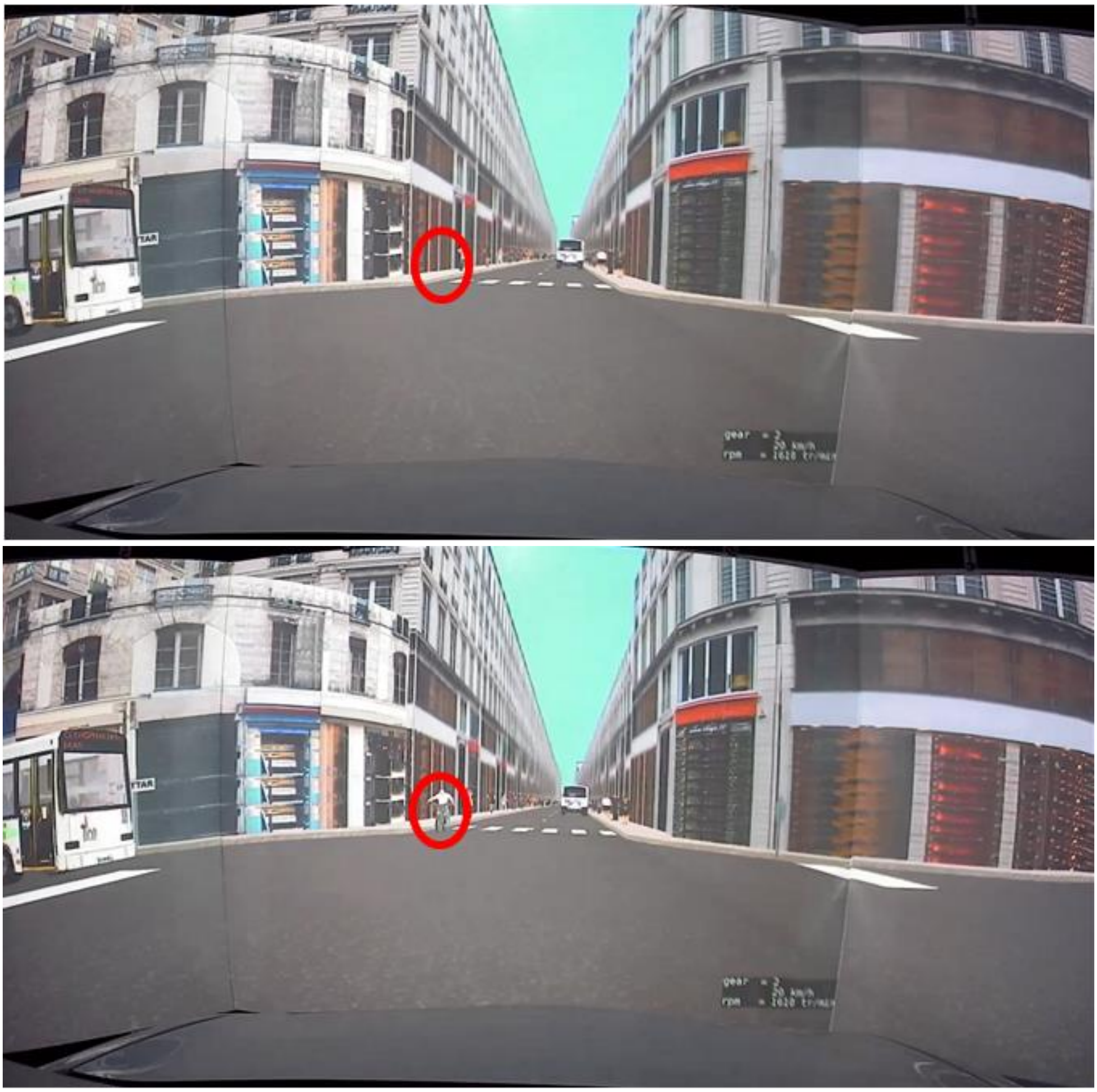


Figure 130: Images of the TL-CR scenario before and after the cyclist appearance

The final new TL-PL critical situation is similar to the one described in section 3.3.5. Participants have to perform 4 audio-cognitive tasks instead of 2 including the one during the critical situation. The task can be triggered not only during a turning manoeuver.

The audio-cognitive secondary task remains similar to the one described in section 3.4.2 except for one point. Only the digits' series are changed. In the new scenarios, calculi are only composed of digits from 5 to 9 instead of digits from 0 to 9 making the calculus more difficult. The task number has also been increased from 2 to 4 for each scenario.

Similarly to the protocol described in section 3.7.2, there is only one major difference. In this additional experiment, there is absolutely no mention of a FCW before or during the experiment. During the recruitment process, people are invited to participate in a study without knowing the real goal of the research. Additionally, for participants who experiment scenarios with a FCW trigger, the experimenter does not give any information relative to the FCW device before the end of the experiment after the debriefing. Thus, participants discover by themselves the FCW device with its 2 signals.

3.9.2 Results

Three people have simulator sickness among the 37 participants.

3.9.2.1 New Turning Left Pedestrian Left (TL-PL) scenario

The Table 32 summarizes the results of the two modalities for this scenario. Participants who have not fully released the gas pedal or have not triggered the brakes are not considered in the calculus of the mean value as participants who react too early.

Among the 18 participants who took part to the without FCW modality, 7 data are excluded due to progressive braking not corresponding to an emergency braking and 1 due to record failure.

Among the 16 participants for the FCW 2s modality, 5 data are excluded due to progressive braking not corresponding to emergency braking. Additionally, 1 data is excluded from the gas release time because of too early reaction and 2 data due to no brake activation.

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	2	-2.95s	0.794	-2.265s	1.018	- 10 fully distracted	18
FCW 2s	3	-2.419s	1.018	-1.500s	0.575	- 10 fully distracted - 1 not distracted	16

*SD = Standard deviation

Table 32: Results data for the new TL-PL scenario

In Table 33 there are estimations of the potential driver reaction time. As for the main campaign, it is hypothesized that the driver reaction is due to the FCW which may not be currently the case. Participants who have released the gas pedal and have braked before the collision have been considered in the results presented below. It corresponds to only 3 participants. Thus, results have to be considered with caution as the dispersion can be important and due to the sample size.

	FCW 2s	
	Gas release duration (s)	Brake trigger duration (s)
Mean	0.7317	1.0323
Standard deviation	0.1393	0.1042
Upper limit	0.8710	1.1366
Lower limit	0.5924	0.9281

Table 33: Driver reaction times for new TL-PL with a FCW 2s

Comparison between without and with FCW 2s

- Number of accidents

There are 2 accidents out of 10 participants without FCW which represents 20% whereas there are 3 out of 11 with 2s FCW trigger (27%).

The two participants who collides without FCW declared that the driving situation very stressful or was completely surprised by the crossing pedestrian. The participant who found the situation stressful released the gas pedal 1s prior the impact and had not braked.

Three participants hit the pedestrian with the FCW signal. One participant declared having seen the pedestrian at the impact. One other participant had seen the pedestrian late because of the A-pillar. The last one declared still having difficulty to handle turning manoeuver.

Due to the low accident rate for the without FCW group, it appears that this new setting is not critical enough to lead to collision with the pedestrian. Even with a more complex audio-cognitive task, reproducing this accident in a driving simulator will require further investigation. As most participants who avoided the pedestrian declared having seen the pedestrian begins to cross and reacted accordingly, it is difficult to evaluate the effect of FCW on a situation that does not lead to an accident. Thus, the current designed scenario will require adjustments.

- Gas release time

An ANOVA test has been performed and it appears that the H0 hypothesis (mean value with and without FCW are equal) is not rejected, **$F(1,21) = 4.32$; $p = 0.214$**.

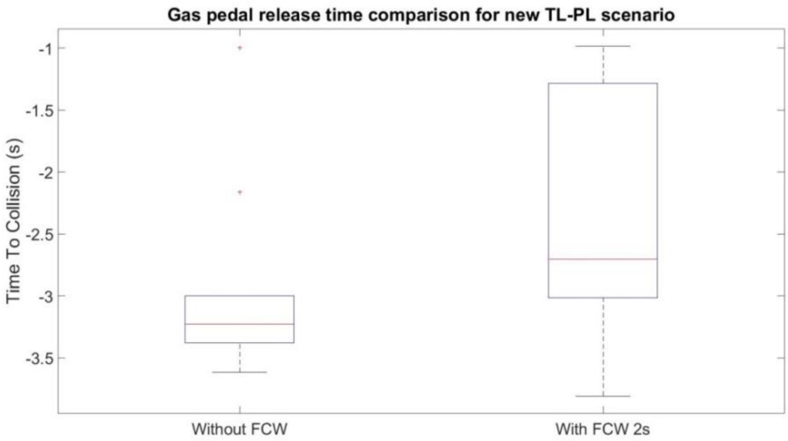


Figure 131: Gas release time for new TL-PL scenario

- Brake trigger time

An ANOVA test has been performed and it appears that the H0 hypothesis (mean value with and without FCW are equal) is rejected, **F(1,18) = 4.41; p = 0.002**.

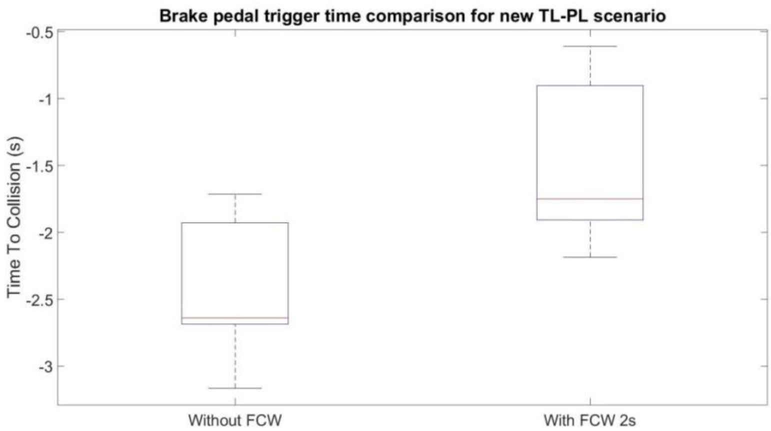


Figure 132: Brake trigger time for new TL-PL scenario

Gaze analysis complement

A gaze analysis complement has been performed on participants who hit the pedestrian.

2 participants without FCW hit the pedestrian. For one of them, the gaze is located on the left during the turning manoeuver. This participant did not react until the impact. For the other one, the participant cut the bend at the intersection and hit the pedestrian on the opposite way. The gaze located on the right side of the windshield at first stayed in front during the turning, manoeuver.

Conclusion for the new TL-PL scenario

Low collision number is observed for this new scenario with a more complex task. This indicates that a more difficult task can lead to more collision. However, the collision proportion is still low revealing that the situation can still be managed to avoid collision. Results for this new scenario show that drivers still have reacted very early more than 2s prior the theoretical impact in agreement with the previous TL-PL scenario results. Driver attentional resources were sufficient despite the new distraction task. This suggests that FCW could have little or no effect for this situation. Nevertheless, estimation results of potential reaction to a FCW can be extracted for this scenario and are consistent with other results from the previous experimental study. Driver's braking reaction time for this scenario ranges from 0.9s to 1.1s

More explorations about drivers' reaction by in-depth investigation team might be of great help to first identify all the element involving the driver and how to reproduce them.

About drivers' reaction, no statistical difference is observed about the time to release the gas pedal. However, a statistical difference is found for the time to depress the brake pedal. With a FCW 2s, drivers appear to react later compared to the without FCW modality. This result has to be considered with caution as our sample is small and as this situation is not perceived as leading to an accident.

3.9.2.2 New TL-CR scenario

The Table 34 below summarizes the results of the two modalities for this scenario. Participants who have not fully released the gas pedal or have not triggered the brakes are not considered in the calculus of the mean value as participants react too early.

Among the 18 participants who took part to the without FCW modality, 4 data are excluded: 2 participants have not noticed the dangerous situation and 2 have not done an emergency braking but a progressive braking. 3 participants have released the gas pedal more than 3s prior the theoretical impact and are not included in the calculus of the mean value. 2 data are excluded for the brake depression time due to one participant who has braked more than 3s before the theoretical impact and one participant who has not braked at all.

Among the 16 participants who took part to the FCW 2s modality, 5 participants are excluded due to too important speed variation from the cyclist appearance to the theoretical impact or due to technical issue. 3 additional data are excluded from the mean calculus: 2 for the time to release the gas pedal and 1 for the time to trigger the brakes.

	Accident number	Mean gas pedal release time	SD*	Mean brake trigger time	SD*	2nd task realization	Total data number
Without FCW	6	-1.282s	0.847	-0.766s	0.486	- 14 fully distracted	14
FCW 2s	7	-1.16s	0.702	-0.779	0.447	- 11 fully distracted	11

*SD = Standard deviation

Table 34: Results data for the new TL-CR scenario

Values presented in Table 35 show estimations of the potential driver reaction time. It corresponds to only 7 participants.

	FCW 2s	
	Gas release duration (s)	Brake trigger duration (s)
Mean	1.1123	1.4199
Standard deviation	0.2302	0.2407
Upper limit	1.3425	1.6605
Lower limit	0.8821	1.1792

Table 35: Driver reaction times for new TL-CR with a FCW 2s

Comparison between without and with FCW 2s

- Number of accidents

There are 6 accidents out of 14 without FCW trigger which represents 43% whereas there are 7 accidents out of 11 with a 2s FCW trigger (64%).

The new settings for this scenario increase the collision rate for the without FCW group with the help of the cyclist sudden appearance. However, not all participants collide with the cyclist showing that the scenario can be improved. Nevertheless, that parameter may also have a side effect on the participant group with FCW. Indeed, a similar accident rate can be observed even with the triggering of a warning message. Participants experienced the critical driving situation and the FCW warning at the same time. On the one hand, the surprise allows the avoidance of anticipation behavior. Even with drivers scanning the surrounding environment before initiating a turning manoeuver, this element of surprise can correspond to "look but fail to see". On the other hand, this may have biased the effect of FCW by cancelling it. Some may consider here that FCW has no effect due to the discovery of the FCW. However, half of the participants involved in a collision experienced that scenario at their 2nd driving scenario. This shows that the scenario order has no influence on reaction on the FCW. Theoretically, FCW should have positive effect on drivers. However, the current results indicate no benefits for the device. Further investigations for this scenario will be required in order to better understand how to reproduce this scenario in a driving simulator and FCW effect only on drivers' reaction.

- Gas release time

An ANOVA test has been performed and it appears that the H0 hypothesis (mean value with and without FCW are equal) is not rejected, **F(1,20) = 4.35; p = 0.73**.

Figure 133 shows the boxplot for those two groups.

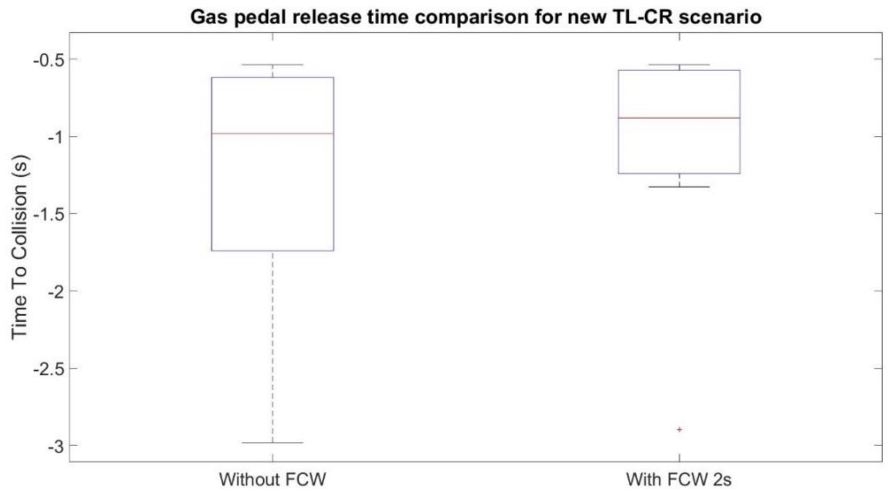


Figure 133: Gas release trigger boxplot for the new TL-CR scenario

- Brake trigger time

An ANOVA test has been performed and it appears that the H0 hypothesis (mean value with and without FCW are equal) is not rejected, **F(1,22) = 4.30; p = 0.95**.

Figure 134 shows the boxplot for those two groups.

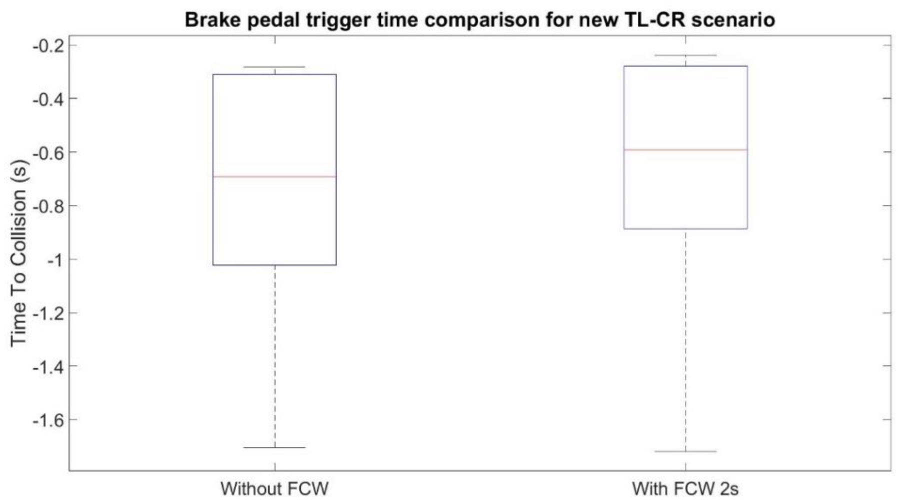


Figure 134: Brake trigger time for new scenario TL-CR scenario

Gaze analysis complement

A gaze analysis has been performed on participants who impact the cyclist. Among the 8 participants who had collided with the cyclist without FCW, 2 of them had not perceived the situation before the impact. For all 8 participants, their gazes were orientated to the left when the cyclist appeared. They were looking at the direction where they were going to. For some of them before the turning, they did make visual check at the intersection before engaging their car in the intersection with glance in front or to the right side. The cyclist was perceived late.

7 participants hit the cyclist with a FCW 2s. Similarly to participants without FCW, their gazes were oriented to the left. The cyclist was perceived during the turning manoeuver.

Conclusion for new TL-CR

Making the cyclist suddenly appears 2.2s prior the theoretical impact highly increases the number of collisions compared to the previously designed version of this scenario. About one out of two participants now collides with the cyclist without and with FCW also affecting the accident rate even with the FCW trigger. A sudden appearance of the cyclist might be a compromise to cause accident allowing to now estimate driver's reaction time to a FCW. The results indicate longer time to react to a FCW signal. However, this is not realistic as in real accident the cyclist might already be in drivers' field of view even if it is not perceived and detected. This estimation results should be considered with caution. Indeed, participants were not aware of the true objective of this experiment combined with the emission of an unknown signal in an a priori not dangerous situation. The combination of both elements might be responsible of a delay in their response ranging from 1.2s to 1.7s.

Concerning drivers' reaction, no statistical difference has been observed either for the gas release time or the brake activation. Results have to be considered carefully because of the cyclist appearance. Further investigations are required to determine if the current results for FCW effect can be biased due to the sudden appearance of the cyclist.

3.9.3 Feedbacks on FCW

A total of 16 participants experiment the FCW trigger 2s prior the theoretical impact.

Concerning the feedbacks about the audio signal, six participants give a positive feedback (**38%**), 5 are mitigated or improvement (**31%**), 4 are negative feedbacks (**25%**) and 1 participant has given no opinion (**6%**).

Positive feedbacks indicate no need of modification of the current signal. Mitigated remarks correspond to participants who are not totally satisfied of the current beep signal but not unsatisfied either. Sometimes, a suggestion is given like playing the sound louder, a clear and distinct sound corresponding to a danger. Negative feedbacks express a preference for another type of signal or people who are not convinced by the current signal.

About the visual signal feedbacks, two participants give a positive feedback (**13%**), 9 participants are mitigated (**56%**), 4 negative feedbacks (**25%**) and 1 no opinion (**6%**). Positive feedback corresponds to signal with no need for modification. Mitigated corresponds to adjustment needed like message positioned too low, switch the message 'brake' by the message 'stop' or by a sign or message that is not attractive enough. Negative feedbacks indicate that the signal is not attractive enough and can possibly distract or disturb because of the unknown trigger reason. It also indicates that the message may not be perceived.

About the triggering timing feedbacks, two participants give a positive feedback (**13%**), 5 mitigated remarks (**31%**), 4 negative feedbacks (**25%**), 3 no opinions (**19%**) and 1 feedback (**7%**) cannot be classified.

Positive feedbacks indicate no need of timing modification. Mitigated remarks indicate that the FCW should trigger earlier. Negative feedbacks clearly indicate that FCW must trigger earlier.

Participants' global feedbacks are summarized here. Participants were not informed of the presence of a FCW device nor of its functioning. They discover it during the driving. In majority, the device needs to be improved either for the visual or the audio signal. The trigger timing has to be modified as only few people are satisfied with the current trigger timing 2s prior the theoretical impact.

3.9.4 Additional experiment conclusion

- The addition of a more complex audio-cognitive task might lead to an increase of collision as it can be seen on TL-PL scenario. Investigations are required to determine how to make the scenario more critical to lead to more accidents by environment changes (pedestrian appearance, obstruction). Reproducing drivers' state of mind at the moment of the turning accident might also be investigated to help reproducing them on a driving simulator. In our scenario, driver appears to still have sufficient attentional resources to manage correctly the situation.
- The sudden appearance of a VRU close to the theoretical impact time increases the risk of collision as shown in TL-CR scenario. This point has to be considered carefully as it also leads to more accident even with a FCW 2s. Further investigations are required about this point.
- No statistical difference can be observed except for the time to depress the brake pedal for the TL-PL scenario. This effect has to be considered with caution due to the sample size and to previous mentioned interrogation.
- Feedbacks about the FCW indicate that the presented signal needs to be improved. Both visual and audio messages as the timing trigger need to be reworked.

- Potential driver reaction times have been extracted per scenario. It has to be reminded that those results relay on the hypothesis that driver reactions have been triggered only thanks to the FCW. Table 36 summarizes results when considering all data for a FCW 2s trigger. It highlights that braking time to react to the FCW goes from 1s to 1,6s. As a recall, data for the FCW 2s contains 10 data (7 from TL-CR, 3 from TL-PL). Results may be biased and may reflect TL-CR scenario due to the bigger sample. It can be observed that driver times to initiate brakes are longer compared to the results obtained previously for the same FCW trigger (Table 31). This may be caused by several elements like the sudden appearance of the cyclist which was no visible a few second before the collision or by the increase of the secondary task difficulty. The combination of a more complex environment and a more difficult task might be responsible of delaying driver response times. However, additional investigations will be necessary in order to confirm those results.

	All FCW 2s	
	Gas release duration (s)	Brake trigger duration (s)
Mean	0.9981	1.3036
Standard deviation	0.2708	0.2745
Upper limit	1.2689	1.5781
Lower limit	0.7273	1.0291

Table 36: Potential driver reaction times to a FCW split according to FCW trigger times for the new scenarios

3.10 Global conclusion

Based on the chapter 2 accident analysis, some accident scenarios have been reproduced for a driving simulator study with 180 participants spread into 2 groups: 143 participants in the main experiment group and 37 for an additional experiment. These scenarios were reproduced and tested with and without FCW signal for two different FCW trigger time (1.7s and 2s). For each scenario, a secondary distraction task has been used few seconds prior the theoretical impact. A visual-cognitive task was used for Longitudinal scenarios whereas an audio-cognitive one was used for Turning situations.

The analysis for the 143 participants reveals no statistical difference for the time to release the gas pedal and the time to depress the brake pedal between the group with and without FCW except for the TR-PR scenario. For this scenario, a statistical difference is observed only for the time to release the gas pedal indicating that participants with a FCW 2s tend to release earlier the gas pedal. However, even with a faster reaction to release the gas pedal, no statistical difference can be observed for those participants for the time to depress the brake pedal compared to the other groups. One interesting point to highlight concerns reaction time in Longitudinal scenarios. Based on the distraction level, our study shows that the more distracted drivers are in a critical situation, the slower they react. This intuitive result is confirmed here. General participant feedbacks about the current presented FCW (audio-visual signal and trigger timing) indicate that the FCW signal needs to be reworked and improved.

For the additional experiment, it concerns only two scenarios: TL-CR and TL-PL, the distraction task difficulty has been increased and the cyclist suddenly appeared. That modification was intended to increase the collision rate with the VRU and also avoiding as much as possible an anticipation reaction. The analysis results for the TL-CR scenario reveal that the sudden cyclist appearance indeed highly increases the collision rate without FCW. However, that element may also have affected the collision rate even with the trigger of a FCW signal with similar accident rate. This might have affected the FCW effectiveness and its perception by drivers who indicate that FCW need to be reworked and improved. For TL-PL the collision rate was still low even without FCW signal suggesting that a harder task could increase collision rate.

For both participants from the main and the additional experiment, results reveal that reproducing accident scenarios is particularly challenging especially for turning scenarios. Simply adding a distraction task to divert drivers' attention away from the VRU in order to lead to a collision appears to be more difficult and complex. When driving straight forward, it might be an evident solution but not necessary in turning manoeuver. It appears that drivers still have sufficient attentional resources in turning which need to be further investigated for the generation of turning configuration accidents. The main difficulty when using a distraction consists not only on the choice of the distraction but also on the instructions given to participants. Indeed, depending on the instructions, it may also have side effect on reaction towards FCW. On the one hand, it is necessary to give instructions to participants to perform the distraction task. On the other hand, those instructions should not interfere with the FCW signal. Indeed, based on the instruction speech, people might be willing to be distracted instead of prioritizing driving. Thus, instructions might introduce a strong bias in driver response to a FCW indicating no effect of a FCW. As an example, let imagine an experiment in which participants get an extra money reward for the realization of the distraction task. If a hazard is triggered when a secondary task is in progress, participants may prefer to focus on the task and to collide with a VRU instead of prioritizing safety. Further investigation will be required either to better understand driver's behavior and state of mind during a turning manoeuver that lead to a collision. Accidents are rare events and their reproductions are far from easy as three main components have to be considered: the environment, the VRU and the vehicle controlled by the driver. By reproducing two of those components in our driving simulator (the environment and the VRU), it remains difficult to recreate even artificially the driver component.

Additionally, this study allows the extraction of the time to release the gas pedal and the time to depress the brake pedal based on the theoretical time to impact. We were not able to extract the drivers' reaction time i.e. the duration from the event onset to the gas pedal release beginning or to the brake pedal depression. This can be explained by the impossibility to identify that onset based on the current data collection due to the gaze being outside the eye tracker field of view. Similarly to the gaze analysis, determining the exact moment when the hazard is perceived is challenging in such situation where the driver is handling a complex task (the turning manoeuver) and as this manoeuver requires constant adaptation.

Under the hypothesis that participants who experienced scenarios with a FCW activation have reacted to the FCW, a potential estimation of driver responses have been nevertheless computed. It can be observed from the main experiment that drivers potentially tend to take between 0.21s to 0.83s to release the gas pedal with a FCW that will trigger 2s before the impact. They also potentially tend to take between 0.66s to 1.28s to initiate a braking. When triggered 0.3s later (FCW 1.7s) it appears that drivers potentially tend to take more time to release the gas pedal and also to initiate a braking. This counterintuitive result has to be considered with caution. It results might be caused by our participant sample and need to be further investigated. In a similar way, the time to initiate brakes is higher in the additional experiment for the FCW 2s compared to the time extracted in the main experiment. The values range from 1.02s to 1.58s. This can be explained by the more complex driving environment which leads to a higher cognitive demand, and then to longer reaction time. Further investigations and researches will be required in order to find a method to determine precisely a reference for the calculation of reaction time in such driving condition. However, driver's reaction time estimation results have been used in chapter 4 for the FCW benefit estimations ranging from 0.6s to 1.6s.

From the literature, some drivers' reaction time towards a FCW system can be found. However, most of them are situations not necessarily involving VRU. Lylykangas et al. (2016) analyzed the effect of tactical, visual and tactical-visual FCW in a vehicle braking task alone. They found that braking reaction time (BRT) was around 800ms with a better effect when the signal includes the tactical signal. During their trial session, those participants were informed to react to a signal that had been explained to them before. Abe and Richardson (2006) analyzed reaction in a follow vehicle task with FCW. They found that baseline mean time to release the gas pedal is 0.72s. They also found that the mean values for braking time can go up to 1.2s depending on the headway. Those reactions time are common to what can be generally considered as a driver mean reaction.

This study reveals the challenges and issues encountered during the scenario reproduction in a driving simulator. It also highlights the difficulties to reproduce the driver component. Our results show nearly no statistical differences for drivers' reaction with or without FCW. However, in order to evaluate the potential benefits of FCW system, different reaction time will be considered. Based on the results obtained in chapter 2, the FOV parameter will be considered from 30° to 70°. From results obtained in this chapter, the FCW trigger times will be considered from 1.7s to 2.6s based on participants' feedbacks who found the trigger too late. Last but not least, the driver reaction time parameter will be taken from 0.6s to 1.2s based on potential driver reactions extracted from the driving simulator experiment. Next chapter presents a simulation software with the introduction of a FCW device in order to determine their effect on accident kinematics.

4. Benefits evaluation for FCW

This chapter presents the results of the benefit estimation for different VRU and per scenario. Through the variation of 3 different parameters, the simulation method integrating the FCW system is described on real-world accident cases. Simulation result is expressed in terms of accident avoidance. Additionally, a parametric analysis is presented, revealing the influence of each parameter on the avoidance rate. Finally, comparisons between scenarios and or VRU are done highlighting the common points and differences.

4.1 Methodology

To be able to evaluate the FCW effect on accident cases during this thesis work, a tool has been developed. This tool aims at determining the potential benefits of the system by determining if an accident can be avoided or mitigated. The developed simulation tool is inspired from Hamdane et al. (2016). The software is developed in Matlab 2012b (Matlab 2012) and requires the Matlab Database toolbox. The software is applied on both French EDA and German GIDAS-PCM databases.

The general simulation algorithm is presented describing in details its content and then the different parameters for the parametric analysis. In this work, we do not focus on the VRU identification, tracking nor on the collision prediction. Thus those elements are not taken into account as it depends on sensors that composed the FCW system, the data processing process and so on. Consequently, this study will consider an optimistically point of view because it will consider an optimal detection.

4.1.1 Accident simulation method integrating FCW effects

The first step consists of gathering the original accident data necessary for the simulation. The data frequency is 100 Hz which corresponds to data every 0.01s. Those data are the kinematics of the car and the VRU and objects in the surrounding environment. The objects will be useful to determine when the VRU can be seen from the vehicle point of view. The kinematic composed of position and speed at each time step will be used to determine the VRU relative position to the car. It will also be used in the calculus of the new vehicle position and speed when adding the FCW effect.

Based on the car positions, the range and FOV of the FCW are overlaid on the car trajectory to determine whether the VRU is inside the FCW detection cone. A 50m detection range is considered in all simulations as a range that can be easily reached by current sensor technology (Mukhtar et al. 2015).

Additionally, the VRU occlusion along the time by elements in the surrounding environment is considered. FCW can be triggered at a pre-defined theoretical time under the conditions that the VRU is in the FCW field of detection and not obstructed by objects in the scene. In the event that the VRU is occluded, the FCW triggering will be delayed to the first time when VRU becomes visible again (see Figure 135). This way, it is possible to determine in the algorithm the moment when the FCW message is delivered to the driver. From there, it is also possible to compute brake activation considering some delay depending on the driver's reaction time to the FCW. The driver's reaction is defined as the lag time after the FCW is triggered to activate the brakes. After the brake activation, a brake deceleration profile with a constant deceleration value of -8m/s^2 is applied (see Figure 135). This value corresponds to an ideal braking model without transient state and ideal road surface conditions (Brach and Brach 2005; Byatt and Watts 1981; Lechner and Ferrandez 1990). As an example, a FCW sets at 2.6s prior the theoretical impact time and a driver's reaction of 1.2s will lead to a brake application at 2.6s-1.2s=1.4s Time To Collision (TTC). If the VRU is occluded until 1.9s before the impact, then the FCW will trigger when the VRU becomes visible at 1.9s and the brakes will be applied at 1.9s-1.2s=0.7s TTC.

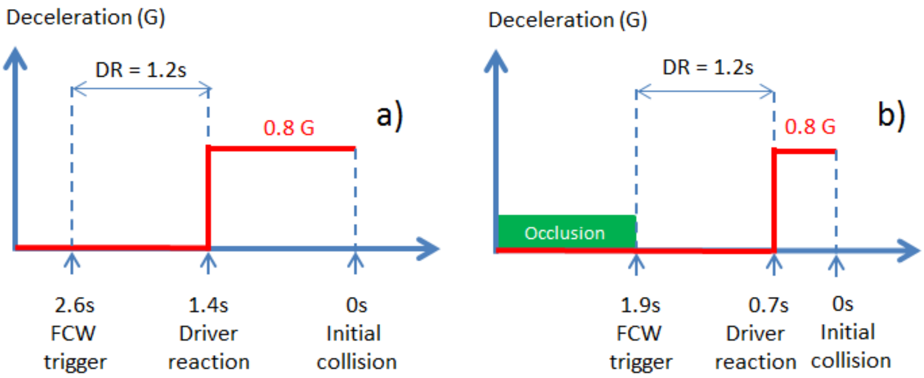


Figure 135: FCW trigger model in the simulation

The calculus of the braking activation will be then used for a comparison with the kinematic of the original accident. If the brake activation happens later compared to the original accident, it is then considered that the FCW has no effect. In that case, the original accident kinematic is kept. Otherwise, the original kinematic is replaced by the newly computed kinematics from the brake application time:

- Car new instantaneous speeds are computed from the brake activation using the ideal braking deceleration value.
- Car new positions are computed following the original trajectory but with consideration of the new instantaneous speeds.
- Car and the VRU trajectories are extended linearly after having reached the original impact location based on the last known segment before the impact until

the car stops. As the car takes more time to reach the original impact location, it is necessary to extend both trajectories in order to define correctly the simulation ending.

- Based on the newly computed kinematics of the car and the VRU and their dimensions, it is determined if a collision is avoided, mitigated or if there is no effect. The bounding boxes of both involved are used to determine if they intersect or not. If they do not intersect, the accident is avoided. Otherwise, the accident is mitigated. The car dimensions are those of the car involved in the real accident and is defined as a rectangular form. The cyclist dimensions are the ones of a rectangular box of 1900mm length and 500mm width according to Euro NCAP test protocol (Euro NCAP 2019b). The pedestrian dimensions are the ones of a rectangular box of 800mm length and 400mm width according to PCM codebook (VUFO GmbH 2016a).
- In the case of a collision mitigation, the speed reduction is computed.

The Figure 136 summarized the simulation algorithm with the inputs and outputs.

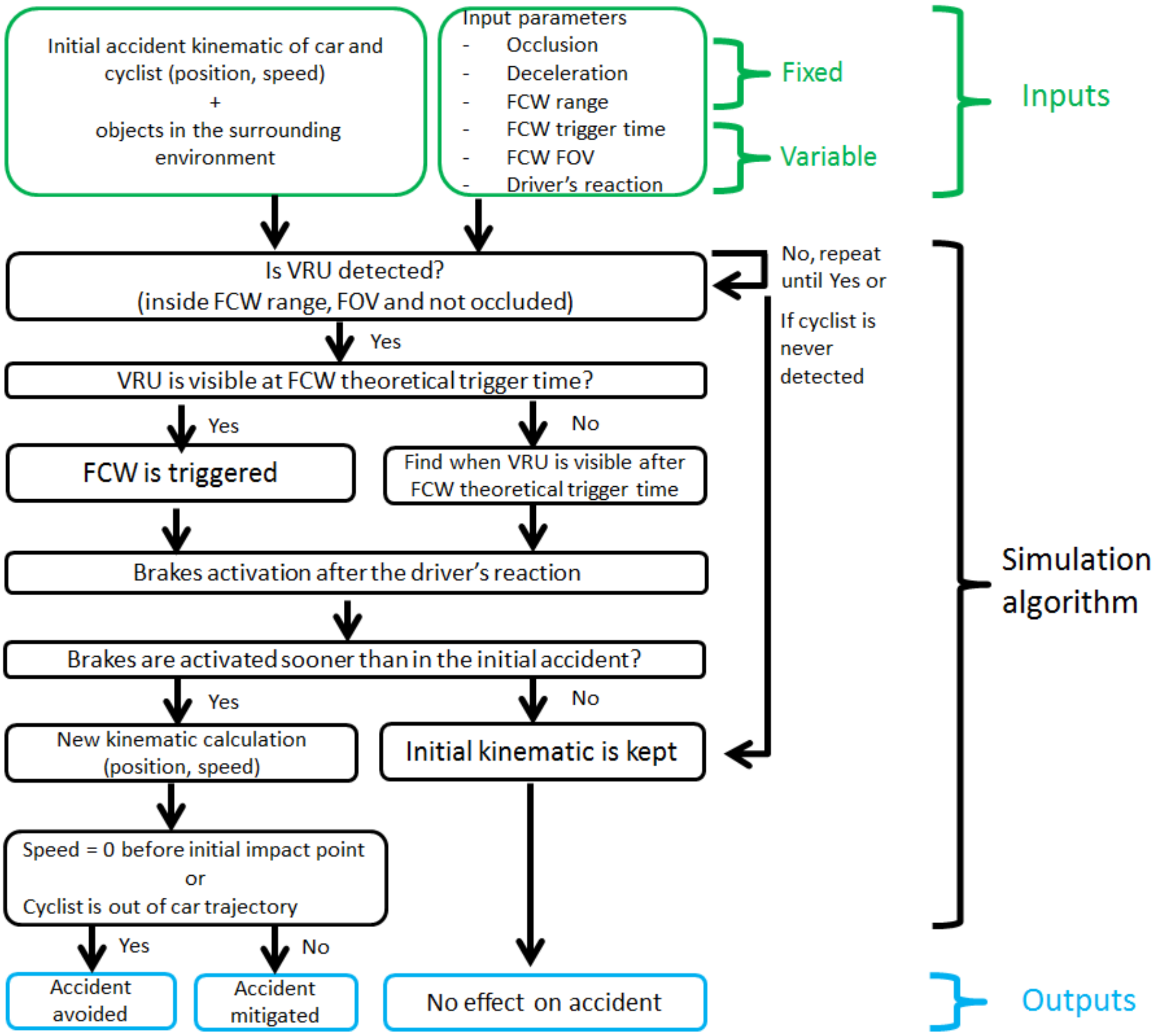


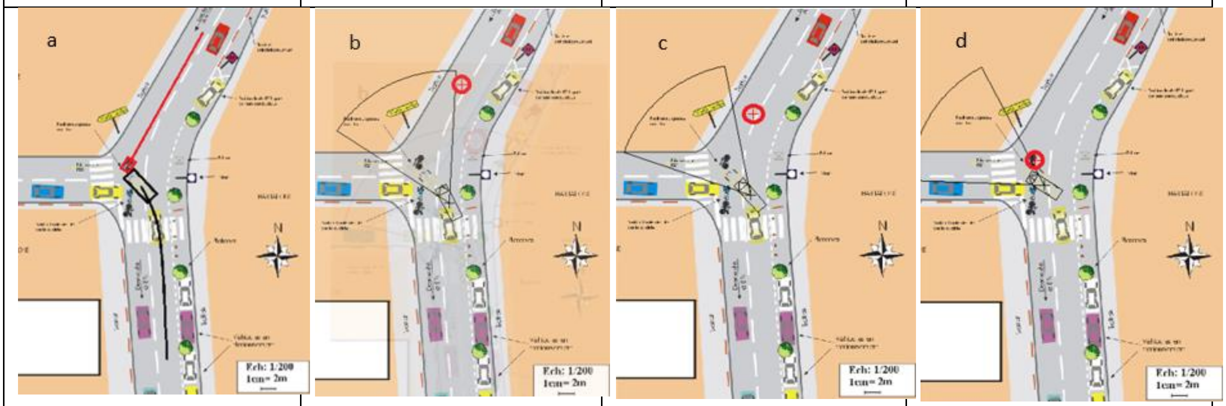
Figure 136: Accident simulation algorithm integrating FCW effect

The Figure 137 illustrates an accident reconstruction from the EDA database with the described algorithm (images a and a') considering for the same accident a FCW with two different FOVs: images b, c and d for a FOV=30° and images b', c' and d' for a FOV=50°. The considered accident case is categorized into the turning left scenario. In this accident, the driver did not brake prior the collision. The original accident kinematics and bounding boxes are in black and red for the car and the cyclist respectively (Figure 137-a and Figure 137-a'). The red circles highlight the different cyclist's position.

For the first simulation with a FOV 30° (total detection cone of 60°), image b represents the car with the detection at TTC 2s. It can be seen that the cyclist is outside the detection cone and thus FCW is not triggered. The kinematic of the accident continues (image c and d) and the cyclist remains outside car's detection cone. This leads to the impact as in the original accident with no trigger of the FCW. This simulation shows as a result that the FCW has no effect with a FCW FOV of 30°.

Image b' represents the car detection cone at TTC 2s. It can be seen that the cyclist is inside the 50° FOV (total detection cone of 100°). Thus FCW warning message is given to the driver at TTC 2s. As in the simulation, the driver needs 0.6s to start braking, the braking is triggered at TTC 1.4s prior the impact (image c'). In image d' which is TTC 0s, it can be seen that the vehicle has stopped earlier. Here the bounding boxes of the car and the cyclist do not intersect. Thus the simulation leads to accident avoidance.

Original accident kinematics	New accident kinematics with FCW (FOV 30°, FCW Trigger 2s, driver's reaction 0.6s)		
TTC 0s	TTC 2s	TTC 1.4s	TTC 0s



Original accident kinematics	New accident kinematics with FCW (FOV 50°, FCW Trigger 2s, driver's reaction 0.6s)		
TTC 0s	TTC 2s	TTC 1.4s	TTC 0s

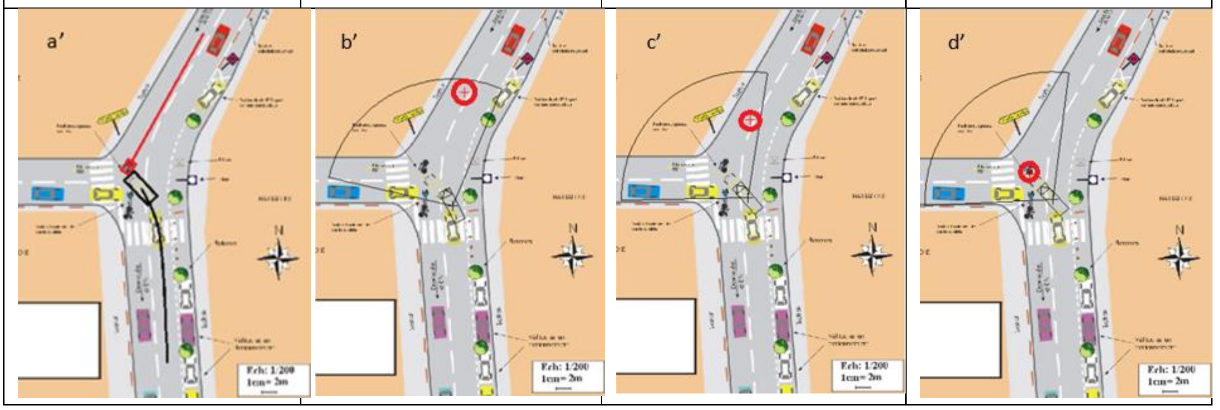


Figure 137: Reconstruction simulation example integrating the effect of FCW for two FCW parameter settings

4.1.2 Parametric analysis

As presented in the previous section, FCW performances can vary depending on detection sensor FOV, FCW trigger time and driver's reaction to the warning. FCW performances can additionally be affected by obstacles obstructing the FOV. In this study, obstruction is kept as in the real accident and no variation is performed on the obstruction and timing. The range is also set with a fixed value of 50m and the ideal braking model is applied with a constant deceleration value of $-8m/s^2$. Therefore the parametric analysis varies only on sensor FOV, FCW trigger time and driver's reaction to the FCW:

- The FOV value corresponds to half of the detection cone, i.e. a FOV 50° corresponds to a detection cone of 100°. The parametric analysis considers three FOV values (30°, 50° and 70°) which correspond to 60°, 100° and 140° detection cone respectively. The choice of those values comes from chapter 2 results and is also motivated by results from Hamdane et al. (2015) which confirm our results. They found that a 35° FOV appears to be optimum for pedestrian. As cyclist speed is higher compared to pedestrian's one, the maximum FOV has been doubled compared to the optimal value found by Hamdane et al. (2015) study and an intermediate value (50°) is chosen in addition.
- The FCW trigger time represents the time-to-collision (TTC) when the warning is emitted if a VRU is detected in the FOV and range of the sensor. FCW trigger times considered in this study are 1.7s, 2s, 2.3s and 2.6s TTC according to the Euro NCAP test protocol (Euro NCAP 2017a; Euro NCAP 2019b) and from results from chapter 3. In those test protocol, the FCW signal should be triggered at least 1.7s prior the theoretical impact time explaining our lowest value choice. The choice of earlier triggering values was linked to our experimental driving study. Even if our experimental study reveals no statistical effect of the FCW, the values could have been compared to those if differences were observed. Additionally, it is interesting to determine how earlier FCW trigger can affect the benefits and to what extent. Indeed in our experimental campaign, volunteers declared that FCW 1.7s or 2s is triggered too late. So it appears interesting to test earlier FCW triggering. The four considered values are theoretical trigger values. FCW trigger time can be latter than these theoretical values if the VRU is obstructed by an object in the accident scene at the time of the theoretical trigger. In this case, the FCW is triggered later when the VRU becomes visible again.
- The driver's reaction time corresponds to the latency between the FCW trigger and the brake application. It corresponds to the time necessary to a driver receiving a FCW to process the information and activate the brakes. The choice of driver's reaction is based on results from our experimental campaign described in chapter 3 and also on a bibliographic review. Bucsuházy et al. (2016) analysed driver's reaction time under expected, unexpected stimulus and under critical braking situation. They found that decision time combined to muscle response time median value was lower than 0.5 second when participants were instructed how to react to a visual stimulus. Johansson and Rumar (1971) analysed driver's reaction time in unexpected traffic situation and found that the median braking response time was 0.9 second. Abe and Richardson (2005) found that the mean braking reaction time was between 0.88 to 1.11s in a car-following situation depending on the trigger time of an alarm and the lead vehicle deceleration (the more critical the situation was, the smaller the reaction time was). Work load effect when phoning

while driving was studied by Haque and Washington (2013). They showed that detecting an event in peripheral vision when engaged in a hand free or a handheld phone conversation was longer compared to no phone conversation condition. Calvi et al. (2015) showed that due to phone conversation, driving performances were reduced in car-following conditions with car speed reduction as compensation. Makishita and Matsunaga (2008) also studied the influence of mental workload for different age groups on driver reaction. They showed that mental calculations which can be represented as a mental distraction close to an intense phone discussion, increased reaction time for all age groups and particularly for elderly drivers. Reaction time could be increased up to 0.5s for elderly drivers whereas for middle and young drivers, the value went up to 0.2s. From our experimental campaign, it could be estimated that drivers could take 0.6s to 1.2s to initiate a braking after a FCW signal is emitted. Considering these studies and results from chapter 3, latencies of 0.6, 0.9 and 1.2s for driver's reaction are considered.

4.1.3 Factor influences on avoidance rates

In order to determine the influence on avoidance rates, a 3 factor ANOVA test has been realized. For the three parameters considered in the parametric analysis, a model is expected to follow the below equation:

$$Avoidance\ (Y) = C + \sum_{i=1}^{n}(a_i x_i) + \sum_{i=1}^{n}\sum_{j=1}^{n}(b_{ij} x_i x_j) + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}(c_{ijk} x_i x_j x_k) \quad \text{(Eq. 2)}$$

where C is a constant, a_i, b_{ij} and c_{ijk} are the coefficients of the model, x_i correspond to the main effect of each parameter, x_i*x_j corresponds to the interaction between two parameters, $x_i*x_j*x_k$ is the interaction effect between the three parameters. The 3 factor ANOVA test will determine if a significant effect on avoidance can be found for each corresponding a_i, b_{ij} and c_{ijk} coefficients or if it can be neglected. However, this method cannot extract the coefficient value for each main interaction and the double or triple factor interactions. The 3 factor ANOVA test is performed using a Matlab script.

4.2 Accident simulations

Appendix E contains the table associated to the parametric analysis for Figure 138 to 142 for pedestrian cases and for Figure 151 to 155 for cyclist cases.

4.2.1 Pedestrian accident cases

4.2.1.1 Simulation effect results on all car-to-pedestrian cases

Effect on kinematics of the 1509 car-to-pedestrian accidents included in PCM and EDA databases was calculated using the simulation tool and considering parameter variations as described previously. Three FOV values, four FCW trigger times and three driver's reaction values are considered leading to 36 simulation sets. In total, 54324 simulations were performed. Figure 138 shows the overall results as the proportion of mitigated cases versus the proportion of avoided cases. The proportion of cases where there is no effect can be obtained by subtracting the sum of the avoided and mitigated cases to 100%.

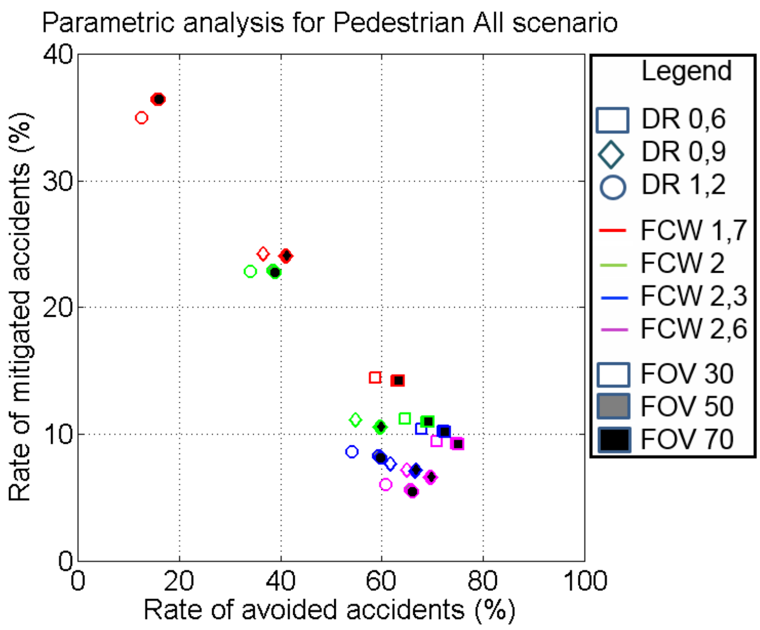


Figure 138: Results of the parametric analysis for all pedestrian accidents (N = 1509)

As expected, earlier reaction (i.e. earlier FCW and quicker driver's reaction) and high FOV maximize avoidance. Later reaction (i.e. later FCW and slower driver's reaction) and high FOV minimizes avoidance but increases mitigation. By combining a 70° FOV with a FCW 2.6s and driver's reaction of 0.6s, about 84% of our sample can be positively affected with 75% avoidance and 9% mitigation. Even with a longer driver's reaction time of 1.2s with the same 70° FOV and FCW trigger time of 2.6s, still 72% positive effect can be observed with 66% avoidance and 6% mitigation. In order to reach a minimum avoidance rate of 50%, it seems that the FCW 2s with a driver's reaction 0.9s is required whatever the FOV.

Interesting results can also be highlighted here. Let us consider two points issued from the figure above, the green diamond with white background and the blue circle with also white background. Both points considered a theoretical braking activation at 1.1s prior the impact (FCW 2s – DR 0.9s or FCW 2.3s – DR 1.2s). However, it can be observed a difference in the simulation between those two points. The difference comes from the occlusion factor. Indeed, even if the theoretical trigger is 2.3s for the blue point, the FCW can actually trigger later due to the occlusion. As a reminder, the reader can go back to Figure 135. Thus, the difference in the obtained effect is due to the longer driver's reaction time which leads to reduce the avoidance and the mitigation effect. Similar observations can be found on scenarios below.

It can be noticed that a non-neglected accident proportion is not affected by FCW (about 16%). Many reasons can explain of that rate. It can be caused by the pedestrian being outside sensors maximum FOV (70°) or sensor range (value fixed at 50m) in the case of car high driving speed. It can be also be caused by driver's reaction in the original accident kinematic. As a reminder, if in the new simulation the driver's reaction with the FCW is later compared to the initial accident, then the FCW is considered as having no effect on the accident case.

Same results split for each identified scenarios in chapter 2 are presented individually.

Pedestrian Crossing Nearside (P-CN)

Figure 139 shows the results for P-CN scenario representing 788 cases (52% of our total sample). For this scenario, avoidance rate goes from 6 to 72% while mitigation goes from 8 to 38%. With the best parameter set considered in this study, about 87% accidents can be positively affected by the FCW with 72% avoidance and 15% mitigation. With regard to the FCW trigger time, more than 50% avoidance rate could be achieved if this parameter is considered to be 2s whatever the FCW FOV if the driver's reaction is less than 0.9s.

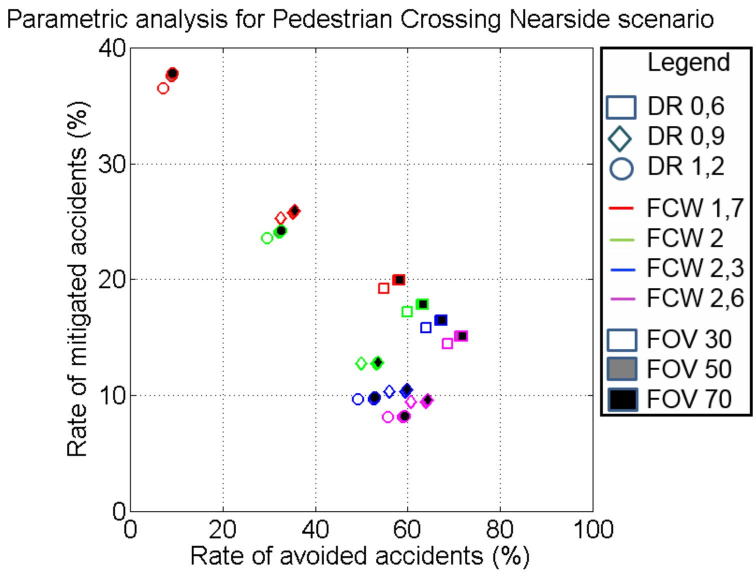


Figure 139: Results of the parametric analysis for the P-CN scenario (N = 788)

Pedestrian Crossing Farside (P-CF)

Figure 140 shows the results for P-CF scenario representing 461 cases (31% of our total sample). For this scenario, avoidance rate goes from 9 to 90% while mitigation goes from 5 to 48%. The best parameter set considered in this study can positively affect 95% accidents with 90% avoidance and 5% mitigation. With regard to the FCW trigger time, more than 50% avoidance rate could be achieved if this parameter is set to 2s whatever the FOV if the driver's reaction is less than 0.9s.

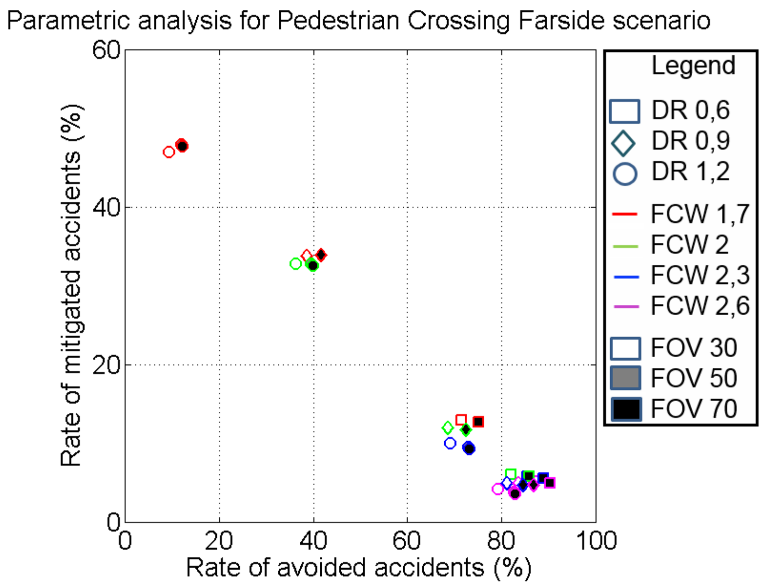


Figure 140: Results of the parametric analysis for the P-CF scenario (N = 461)

Pedestrian Longitudinal (P-L)

Figure 141 shows the results for P-L scenario representing only 20 cases (1% of our total sample). For this scenario, avoidance rate goes from 21 to 90% while mitigation goes from 5 to 63%. The best parameter set considered in this study can affect positively 94% accidents with 89% avoidance and 5% mitigation. With regard to the driver's reaction time, more than 50% avoidance rate could be reached if this parameter is set to 0.9s whatever the FOV and the FCW trigger time.

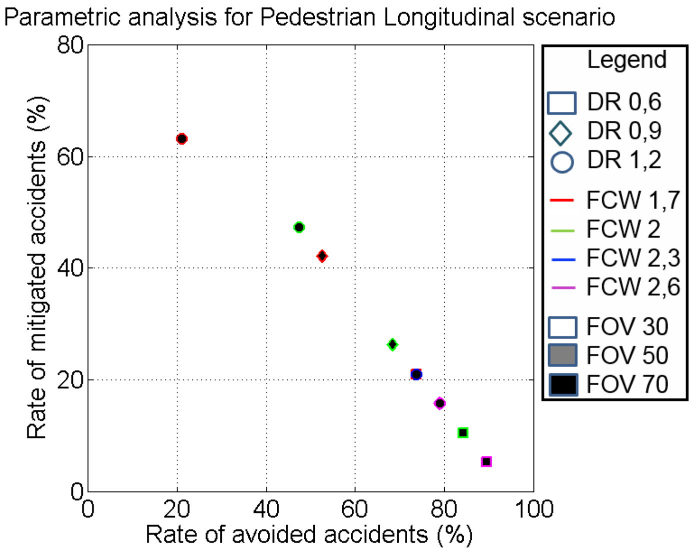


Figure 141: Results of the parametric analysis for the P-L scenario (N = 20)

Pedestrian Turning Left (P-TL)

Figure 142 shows the results for the P-TL scenario representing 124 cases (8% of our total sample). For this scenario, avoidance rate goes from 52 to 95% while mitigation goes from 0 to 18%. The best parameter set considered in this study can positively affect 95% accidents with 95% avoidance and no mitigation. It can be observed that more than 50% avoidance rate could be reached even for the worst parameter set considered in this study i.e. FOV 30°, FCW 1.7s and with a driver's reaction of 1.2s.

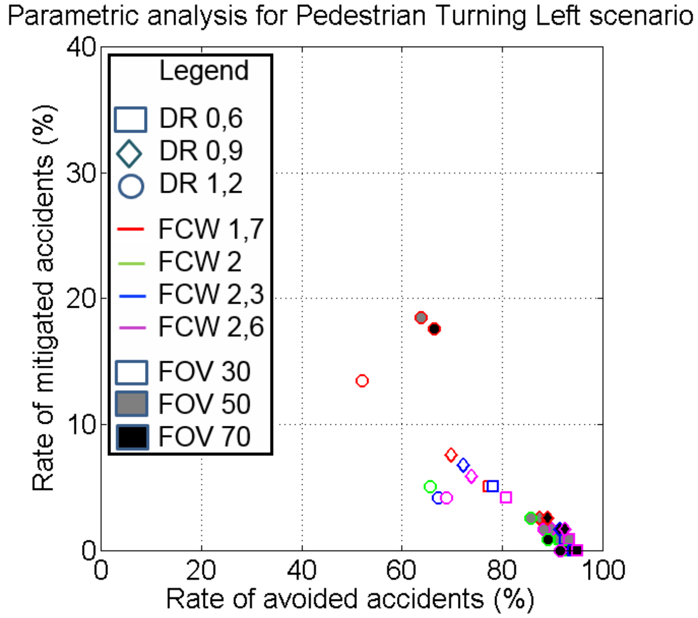


Figure 142: Results of the parametric analysis for the P-TL scenario (N = 124)

Pedestrian Turning Right (P-TR)

Figure 143 shows the results for P-TR scenario representing 55 cases (4% of our total sample). For this scenario, avoidance rate goes from 51 to 92% while mitigation goes from 2 to 26%. The best parameter set considered in this study can positively affect 94% accidents with 92% avoidance and 2% mitigation. As points are drawn sequentially, some points cannot be seen as they are overlaid by the new drawn points. This is the case of points corresponding to FOV 50° which are hidden by points with 70° FOV and also for lower FCW trigger values overlaid by higher values. This indicates that even with variation of our three considered parameters, they have no additional positive effect. This result has to be considered with caution due to the low number of cases for this scenario and may require further investigations with bigger sample.

Similarly to P-TL scenario, a minimum of 50% avoidance can be reached even for the worst parameter set considered in this study i.e. FOV 30°, FCW 1.7s and with a driver's reaction of 1.2s.

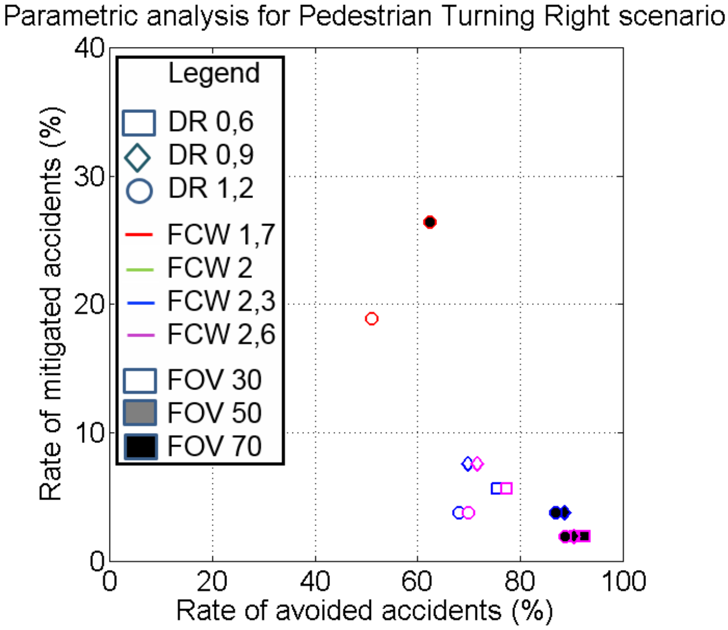


Figure 143: Results of the parametric analysis for P-TR scenario (N = 55)

General conclusion on pedestrian simulation results

In summary, the best parameter set in this study and identified for each scenario can affect about 87% of CN cases (72% avoided and 15% mitigated), 94% CF cases (93 avoided and 1% mitigated), 84% L cases (93% avoided and 1% mitigated), 95% TL cases (95% avoided and 0% mitigated) and 94% TR cases (92% avoided and 2% mitigated). These results show that FCW would have the highest benefit in the CF and the TL scenarios whereas the CN scenario would be the most challenging to optimize FCW parameters. It can be noticed that with a FCW 2s and with a driver's reaction in 0.9s, avoidance rates reach more than 50% whatever the scenario with a mitigation rate up to 26% depending the scenario. Table 37 sums up the parameter values that allow reaching the maximum sum of the avoidance and mitigation rates in all scenarios and at least 50% avoidance rates.

		CN	CF	L	TL	TR
FOV 70°, FCW 2.6s, DR 0.6s	Avoidance rate	72%	90%	89%	95%	92%
	Mitigated rate	15%	5%	5%	0%	2%
All FOV, FCW 2s, DR <0.9s	Avoidance rate	50%	69%	68%	72%	70%
	Mitigated rate	12%	12%	26%	7%	8%

Table 37: Parameter combinations that allow reaching a maximum avoidance and mitigation rate and at least 50% avoidance in most scenarios

4.2.1.2 Car-to-pedestrian factor influence on avoidance

The 3 factor ANOVA test has been applied to the complete pedestrian accident case sample and also per scenario. It aims at determining which parameter between FOV, FCW trigger time, driver reaction or combinations have the most influence. During all this section, the FOV parameter is X1, the FCW trigger time is X2 and the drivers' reaction is X3. X1*X2, X1*X3 and X2*X3 represent the interaction between two factors and X1*X2*X3 represents the interaction between three factors. The information is summarized in the Table 38 below.

Factors	Parameters	
X1	FOV	Parameter main effect
X2	FCW trigger time	
X3	Driver's reaction delay	
X1*X2	FOV + FCW trigger time	Second order interaction
X1*X3	FOV + Driver's reaction delay	
X2*X3	FCW trigger time + driver's reaction delay	
X1*X2*X3	FOV + FCW trigger time + Driver's reaction delay	Third order interaction

Table 38: Correspondence between factors

Pedestrian All cases

Figure 144 shows the results of the 3 factors ANOVA test for our whole pedestrian case sample. "Prob>F" represents the *p*-value. If its value is lower than 0.05 (our significance level) then our single factor or the interaction between factor is significant. The *p*-value for X1, X2, X3 and X2*X3 are significant and reveals an influence on the avoidance rate. X2*X3 which corresponds to the theoretical start braking time has indeed an influence as the sooner the braking is initiated, the better chance you have of avoiding an accident. X1*X2*X3 effect is not significant if at least one of the second order effect is not significant. Here X1*X and X1*X3 are not significant indicating that X1*X2*X3 is also not significant.

Even if it is not possible to extract the coefficient value of the avoided rate, it may be also interesting to have a look at the F value. With consideration to it, the F value indicates the order of importance of the different factors (Snedecor and Cochran 1989). When considering all pedestrian cases, it appears that the driver's reaction delay should be priorized, then the FCW trigger time, then the second order interaction X2*X3 (FCW trigger time and driver's reaction delay) and finally the FOV. The results are summarized in Table 39.

The results clearly indicate that the FOV parameters should be the less prioritized parameters for a FCW system. Indeed, the FOV parameter is less critical in pedestrian cases as the pedestrian displacement speed is slow. As the pedestrian is located closer to the car's path and may already be inside the vehicle detection field. The higher importance of X2*X3 corresponding to the time where the braking start appears obvious as the sooner is the braking, the most chance there is to avoid the accident. This is confirmed by the higher vehicle approach speed as shown in section 2.4.1.1. In a similar way, the main effect of the FCW trigger time and the driver's reaction delay strongly influence the braking time as the braking time is composed of the combination of those two elements. Results can potentially reflect the crossing scenarios as they represent more than 80% of whole sample.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.01697	2	0.00849	869.15	0
X2	0.47876	3	0.15959	16345.95	0
X3	0.37756	2	0.18878	19335.77	0
X1*X2	0.00009	6	0.00002	1.62	0.2245
X1*X3	0.00003	4	0.00001	0.67	0.6261
X2*X3	0.13973	6	0.02329	2385.31	0
Error	0.00012	12	0.00001		
Total	1.01326	35			

Figure 144: Results of the 3 factor ANOVA test for all pedestrian cases (N = 1509)

Order of importance of significant parameters	1	2	3	4
Factors	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time	FOV

Table 39: Factor order of importance for P-All cases (N = 1509)

Pedestrian Crossing Nearside (P-CN)

Figure 145 shows the results of the test for P-CN cases. The results indicate that the three main factors intervene in the avoidance rate with the second order interaction X2*X3 (FCW trigger time and the driver's reaction delay).

With consideration of the F values, the driver's reaction delay has to be prioritized first, the FCW trigger time, the second order interaction driver's reaction and FCW trigger time and finally the FOV. The third order interaction is considered as neglected as at least one second order interaction is not significant. Table 40 summarizes the results.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.00787	2	0.00393	793.86	0
X2	0.48971	3	0.16324	32948.56	0
X3	0.4271	2	0.21355	43103.42	0
X1*X2	0.00008	6	0.00001	2.64	0.0717
X1*X3	0.00003	4	0.00001	1.47	0.2721
X2*X3	0.13184	6	0.02197	4435.16	0
Error	0.00006	12	0		
Total	1.05668	35			

Figure 145: Results of the 3 factor ANOVA test for P-CN cases (N = 788)

Order of importance of significant parameters	1	2	3	4
Factors	Driver’s reaction delay	FCW trigger time	Driver’s reaction + FCW trigger time	FOV

Table 40: Factor order of importance for P-CN cases (N = 788)

Pedestrian Crossing Farside (P-CF)

Figure 146 shows the results of the test for P-CF cases. The results indicate that the three main factors intervene in the avoidance rate with the second order interaction X2*X3 (FCW trigger time and the driver’s reaction delay).

With consideration of the F values, the FCW trigger time should be prioritized with the driver’s reaction delay as their F values are very close. Next, comes the X2*X3 and the FOV. The third order interaction is considered as neglected as at least one second order interaction is not significant. Table 41 summarizes the factor influence order.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.0097	2	0.00485	1767.8	0
X2	1.04626	3	0.34875	127120.6	0
X3	0.66363	2	0.33181	120945.8	0
X1*X2	0.00004	6	0.00001	2.2	0.1155
X1*X3	0.00001	4	0	0.8	0.5479
X2*X3	0.31344	6	0.05224	19041.4	0
Error	0.00003	12	0		
Total	2.0331	35			

Figure 146: Results of the 3 factor ANOVA test for P-CF cases (N = 461)

Order of importance of significant parameters	1	2	3	4
Factors	FCW trigger time	Driver's reaction delay	Driver's reaction + FCW trigger time	FOV

Table 41: Factor order of importance for P-CF cases (N = 461)

Pedestrian Longitudinal (P-L)

Figure 147 shows the results of the test for the P-L cases. The results indicate that four elements have a significant effect on the avoidance rate: the FCW trigger time, the driver's reaction time, the second order interaction X1*X3 (FOV and driver's reaction delay) and X2*X3 (FCW trigger time and the driver's reaction delay).

Figure 148 shows the 3 factor ANOVA analysis without the non-significant factors. With consideration of the F values, the results show that the FCW trigger time should be prioritized, then the driver's reaction delay and finally the second order interactions X2*X3 and the X1*X3. The third order interaction is considered as neglected as at least one second order interaction is not significant. Table 42 summarizes the factor influence order.

Due to the very small sample size (N = 20), extracting reliable conclusion for this scenario should be considered with caution. An analysis on a greater sample is strongly advised.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0	2	0	NaN	NaN
X2	0.64474	3	0.21491	Inf	0
X3	0.50277	2	0.25139	Inf	0
X1*X2	0	6	0	NaN	NaN
X1*X3	0	4	0	Inf	0
X2*X3	0.18421	6	0.0307	Inf	0
Error	-0	12	-0		
Total	1.33172	35			

Figure 147: Results of the 3 factor ANOVA test for P-L cases (N = 20)

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X2	0.64474	3	0.21491	19357577345715288	0
X3	0.50277	2	0.25139	22642751589134188	0
X1*X3	0	4	0	10	0.0001
X2*X3	0.18421	6	0.0307	2765368192245043.5	0
Error	0	20	0		
Total	1.33172	35			

Figure 148: Three factor ANOVA complement without the non-significant factors

Order of importance of significant parameters	1	2	3	4
Factors	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time	FOV + driver's reaction delay

Table 42: Factor order of importance for P-L cases (N = 20)

Pedestrian Turning Left (P-TL)

Figure 149 shows the results for P-TL cases. The results indicate that the three main factors intervene in the avoidance rate with the second order interaction X2*X3 (FCW trigger time and the driver's reaction delay).

With consideration of the F values, the FOV should be prioritized, the driver's reaction, the FCW trigger time and finally the X2*X3 interaction. The third order interaction is not significant as at least one second order interaction is not significant. Table 43 summarizes the factor influence order.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.24625	2	0.12313	487.84	0
X2	0.04818	3	0.01606	63.63	0
X3	0.08461	2	0.04231	167.62	0
X1*X2	0.00122	6	0.0002	0.81	0.5845
X1*X3	0.004	4	0.001	3.96	0.0282
X2*X3	0.05524	6	0.00921	36.48	0
Error	0.00303	12	0.00025		
Total	0.44254	35			

Figure 149: Results of the 3 factor ANOVA for P-TL cases (N = 124)

Order of importance of significant parameters	1	2	3	4	5
Factors	FOV	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time	FOV + driver's reaction delay

Table 43: Factor order of importance for P-TL cases (N = 124)

Pedestrian Turning Right (P-TR)

Figure 150 shows the results for the P-TR cases. The results indicate that the three main factors intervene in the avoidance rate with the second order interaction X2*X3 (FCW trigger time and driver's reaction time) and the X1*X3 (FOV and driver's reaction delay).

With regards to the F values, the FOV should be prioritized, then the driver's reaction delay, the FCW trigger time, finally the X2*X3 and the X1*X3 interactions. Table 44 summarizes the factor influence order.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.23522	2	0.11761	648.71	0
X2	0.04264	3	0.01421	78.4	0
X3	0.07371	2	0.03686	203.29	0
X1*X2	0.00085	6	0.00014	0.78	0.6001
X1*X3	0.00194	4	0.00048	2.67	0.0837
X2*X3	0.0743	6	0.01238	68.31	0
Error	0.00218	12	0.00018		
Total	0.43084	35			

Figure 150: Results of the 3 actor ANOVA for P-TR case (N = 55)

Order of importance of significant parameters	1	2	3	4
Factors	FOV	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time

Table 44: Factor order of importance for P-TR case (N = 55)

General conclusion of factor influence order on pedestrian cases

Table 45 gives a global view on the order of the factor influence according to the scenario. The results on our whole sample are strongly affected by the high case number on the P-CN scenario. However it can be observed for Turning scenarios that the most important effect on the avoidance rate comes from the FOV parameter. Indeed, if the pedestrian is not detected, the FCW system cannot be triggered which appears to be logical. Results on the Longitudinal scenario may not be robust enough due to the small sample size.

Scenario/ Order	1	2	3	4	5	Sample size
P-CN	DR	FCW	DR + FCW	FOV	-	788
P-CF	FCW	DR	DR + FCW	FOV	-	461
P-L	DR	FCW	DR + FCW	FOV + DR	-	20
P-TL	FOV	DR	FCW	DR + FCW	FOV + DR	124
P-TR	FOV	DR	FCW	DR + FCW	-	55
P-All	DR	FCW	DR + FCW	FOV	-	1509

DR = Driver's reaction delay

FCW = FCW trigger time

'+': second order interaction

'-': No additional significant factors

Table 45: Global view of the factor influence order on the different pedestrian scenarios

4.2.2 Cyclist accident cases

4.2.2.1 Simulation effect results on car-to-cyclist cases

Effect on kinematics of the 2261 car-to-cyclist accidents included in EDA and PCM databases was calculated using the simulation tool and considering the 36 parameter variations as described previously. In total 81396 simulations were performed. Figure 151 shows the overall results. The proportion of cases where there is no effect can be obtained by subtracting the sum of the avoided and mitigated cases to 100%.

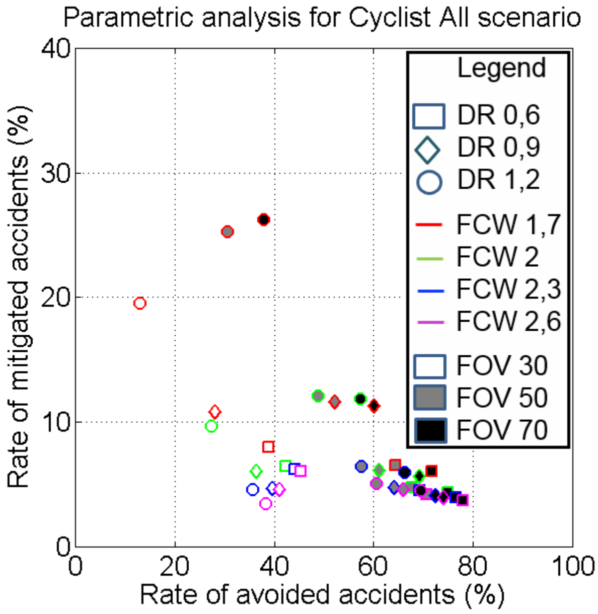


Figure 151: Results of the parametric analysis for all cyclist accidents (N = 2261)

As expected, earlier reaction (i.e. earlier FCW and quicker driver reaction) and high FOV maximize avoidance. Later reaction (i.e. later FCW and slower driver reaction) and high FOV minimizes avoidance but increases mitigation. A 70° FOV combined with a FCW 2.6s TTC and driver's reaction of 0.6s can affect positively 82% of our sample by avoiding 78% of the cases and mitigating 4% of them. Still a longer reaction time of 1.2s for a 70° FOV with a 2.6s FCW trigger allows avoiding about 69% of cases and mitigating 5% of them. To reach at least 50% avoidance, it appears that a FOV 50° is required if drivers react in 0.9s whatever the alarm timing.

Similarly to pedestrian results, it can be interesting to make comparisons between points where the theoretical braking activation is the same. Let consider the blue circle and the green diamond with grey background which correspond to a theoretical braking time of 1.1s prior the impact. The same explanation can be given here as it was the case for pedestrian. Even if an earlier FCW trigger time is considered, the occlusion factor may lead to a later detection and then a later trigger. As the FCW trigger later compared to the FCW trigger parameter value and due to the longer driver's reaction time, it finally leads to less effectiveness. This result indicates that driver's reaction can be more efficient than theoretical trigger time because of the occlusion delaying the trigger time.

It can be noticed that a non-neglected accident proportion are not affected by FCW (about 20%). It can be caused by the cyclist being still outside of the sensors maximum FOV (70°) or sensor range (value fixed at 50m) in the case of high driving speed by the car. FCW has also no effect in our simulations if the brake timing as recorded in the pre-crash databases happened earlier than the one computed by the simulation algorithm.

Same results split for each identified scenarios in chapter are presented individually.

Cyclist Crossing Nearside (C-CN)

Figure 152 shows the results for the C-CN scenario representing 744 cases (33% of our total sample). For this scenario, avoidance rate goes from 11 to 81% while mitigation rate goes from 5 to 25%. With the best parameter set considered in this paper, at least 88% accidents could be positively affected by the FCW system with 81% avoidance and 7% mitigation. With regard to driver's reaction, more than 50% avoidance rate could be achieved if this parameter is considered to be 0.9s, whatever the trigger time of the FCW if the FOV is at least 50°.

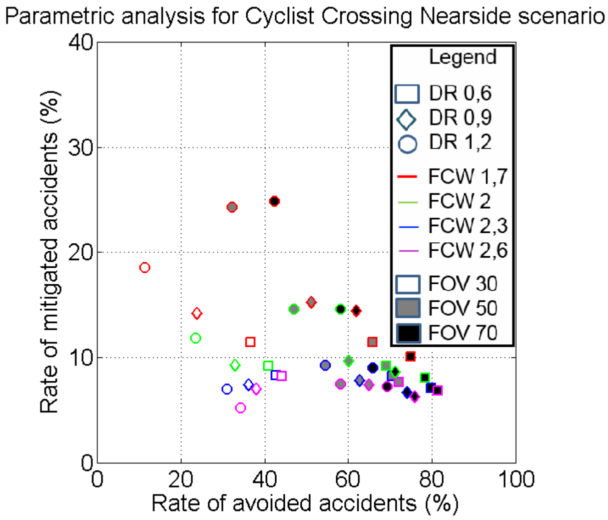


Figure 152: Results of the parametric analysis for C-CN scenario (N = 744)

Cyclist Crossing Farside (C-CF)

Figure 153 shows the results for C-CF scenario representing 504 cases (22% of our total sample). For this scenario, avoidance rate goes from 10 to 93% while mitigation rate goes from 1 to 34%. With the best parameter set considered here, 94% accidents can be affected (93% avoidance and 1% mitigation). 50% avoidance rates could be reached with a FOV of 50° and if the driver reacts in 0.9s whatever the trigger timing of the device.

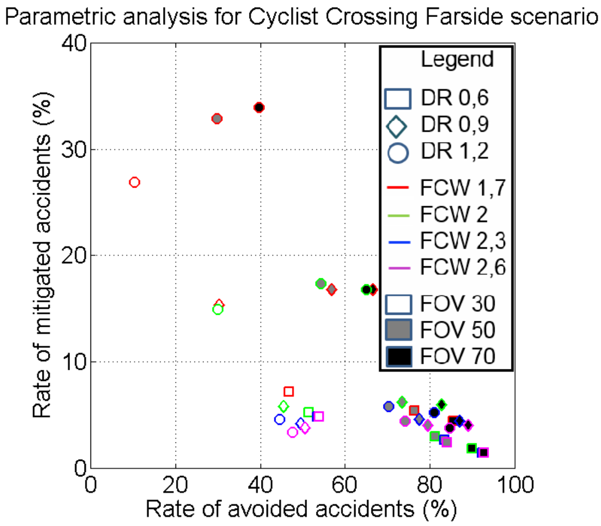


Figure 153: Results of the parametric analysis for C-CF scenario (N = 504)

Cyclist Longitudinal (C-L)

Figure 154 shows the results for C-L scenario representing 120 cases (5% of our total sample). For this scenario, avoidance rate goes from 12 to 81% while mitigation goes from 2 to 53%. With the best parameter set considered here, at least 84% cases can be affected (81% avoidance and 3% mitigation). In this scenario, the FOV influence is not as critical as it can be in other scenarios. As the cyclist may already be in front of the car, then the needed FOV to detect the cyclist can strongly be reduced. A focus on the trigger time and on the driver's reaction is more needed on this particular scenario. It can be highlighted that if a driver reacts in 1.2s, the avoidance rate drops drastically between FCW 2.3s and FCW 2s even if the avoidance rate remains close to 50%.

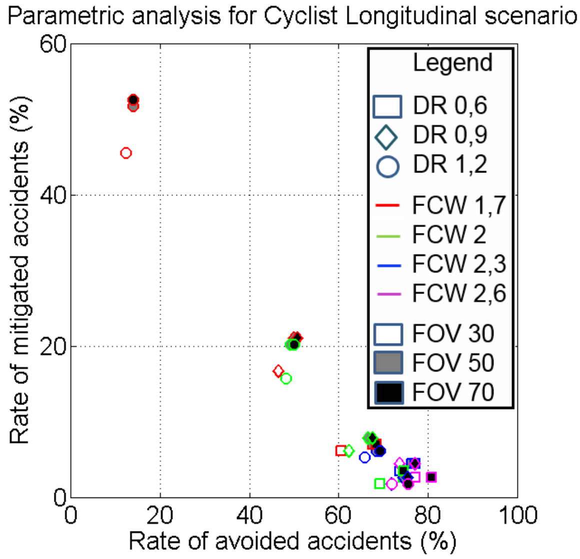


Figure 154: Results of the parametric analysis for C-L scenario (N = 120)

Cyclist Turning Left (C-TL)

Figure 155 shows the results for C-TL scenario representing 280 cases (12% of our total sample). For this scenario, avoidance rate goes from 28 to 87% while mitigation goes from 2 to 30%. With the best parameter set considered here, a positive effect can be estimated for 90% of the cases (87% avoidance and 3% mitigation). It can be noticed that a 50% avoidance rate is reached for the values considered here except if drivers react in 1.2s.

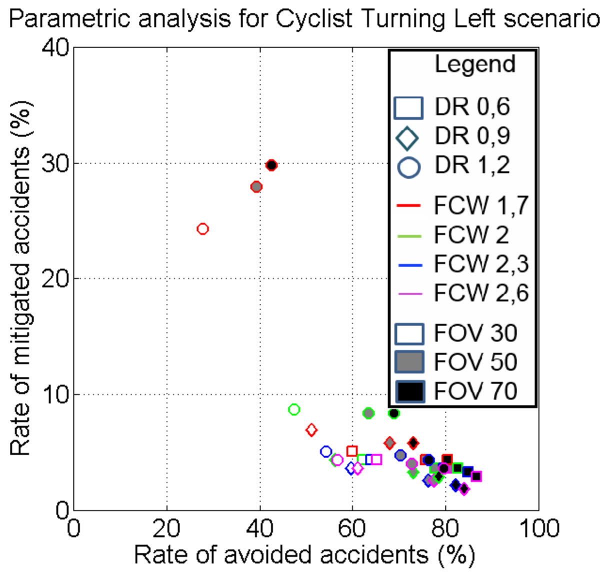


Figure 155: Results of the parametric analysis for C-TL scenario (N = 280)

Cyclist Turning Right (C-TR)

Figure 156 shows the results for C-TR scenario representing 492 cases (22% of our total sample). For this scenario, avoidance rate goes from 14 to 76% while mitigation goes from 2 to 21%. With the best parameter set, positive effect could be observed for 79% cases (76% avoidance and 3% mitigation). A gap can be observed between 30° FOV detection, 50° and 70°. To affect at least 50% of cases, a FOV of 50° is required with a FCW trigger at 2s.

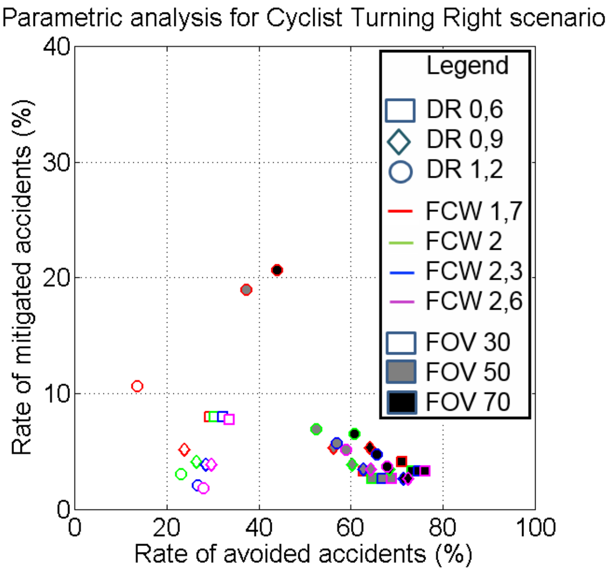


Figure 156: Results of the parametric analysis for C-TR scenario (N = 492)

General conclusion on cyclist simulation results

In summary, the best parameter set in this study and identified for each scenario can affect about 88% of CN cases (81% avoided and 7% mitigated), 94% of CF cases (93% avoided and 1% mitigated), 84% of L cases (81% avoided and 3% mitigated), 90% of TL cases (87% avoided and 3% mitigated) and 79% of TR cases (76% avoided and 3% mitigated). These results show that FCW would have the highest benefit in the CF scenario whereas TR scenario would be the most challenging to optimise FCW parameters. It can be noticed that with a FOV of 50° and with a driver's reaction of 0.9s, avoidance rates reach more than 50% whatever the scenario with a mitigation rate up to 21% depending the scenario. Table 46 sums up the parameter values that allow reaching the maximum sum of the mitigation and avoidance rates in all scenarios and at least 50% avoidance rates.

		CN	CF	L	TL	TR
FOV 70°, FCW 2.6s, DR 0.6s	Avoidance rate	81%	93%	81%	87%	76%
	Mitigated rate	7%	1%	3%	3%	3%
FOV 50°, all FCW, DR <0.9s	Avoidance rate	51%	57%	50%	68%	56%
	Mitigated rate	15%	17%	21%	6%	5%

Table 46: Parameter combinations that allow reaching a maximum avoidance and mitigation rate and at least 50% avoidance in most scenarios

4.2.2.2 Car-to-cyclist factor influence on avoidance

Cyclist All cases

An analysis similar to pedestrian cases has been performed with ANOVA tests in order to determine the influence of each parameter or parameter combination. Results indicate that the three main factors intervene in the avoidance rate as the second order interaction X1*X3 and X2*X3. Results can potentially be biased by crossing scenarios as they represent more than 50% of our whole sample.

With consideration of the F values, it appears that the FOV should be prioritized, then the driver's reaction delay, the FCW trigger time and finally the second order interaction X2*X3 and X1*X3. Results are summarized in Table 47.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.64251	2	0.32126	4778.9	0
X2	0.14218	3	0.04739	705.01	0
X3	0.17213	2	0.08607	1280.28	0
X1*X2	0.00054	6	0.00009	1.35	0.3089
X1*X3	0.00266	4	0.00067	9.9	0.0009
X2*X3	0.05004	6	0.00834	124.07	0
Error	0.00081	12	0.00007		
Total	1.01088	35			

Figure 157: Results of the 3 factor ANOVA test for all cyclist cases (N = 2261)

Order of importance of significant parameters	1	2	3	4	5
Factors	FOV	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time	FOV + driver's reaction delay

Table 47: Factor order of importance for C-All cases (N = 2261)

Cyclist Crossing Nearside (C-CN)

Figure 158 shows the results for C-CN cases. The results indicate that the three main factors intervene in the avoidance rate with the second order interaction X2*X3 and X1*X3.

With consideration to the F values, the FOV should be prioritized, then the driver's reaction delay, the FCW trigger time and finally the X2*X3 and the X1*X3 interaction as summarized in Table 48.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.84721	2	0.4236	8426.79	0
X2	0.12337	3	0.04112	818.05	0
X3	0.21997	2	0.10999	2187.96	0
X1*X2	0.00011	6	0.00002	0.38	0.8811
X1*X3	0.00375	4	0.00094	18.66	0
X2*X3	0.03192	6	0.00532	105.84	0
Error	0.0006	12	0.00005		
Total	1.22694	35			

Figure 158: Results of the 3 factor ANOVA test for C-CN (N = 744)

Order of importance of significant parameters	1	2	3	4	5
Factors	FOV	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time	FOV + driver's reaction delay

Table 48: Factor order of importance for the C-CN (N = 744)

Cyclist Crossing Farside (C-CF)

Figure 159 shows the results for C-CF cases which are similar to C-CN. The results indicate that the three main factors intervene in the avoidance rate with the second order interaction X2*X3 and X1*X3.

With consideration to the F values, the FOV should be prioritized, then the driver's reaction delay, the FCW trigger time and finally the X2*X3 and the X1*X3 interaction as summarized in Table 49.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.8765	2	0.43825	4261.93	0
X2	0.31436	3	0.10479	1019.03	0
X3	0.28494	2	0.14247	1385.52	0
X1*X2	0.00127	6	0.00021	2.06	0.1345
X1*X3	0.00373	4	0.00093	9.06	0.0013
X2*X3	0.11607	6	0.01935	188.13	0
Error	0.00123	12	0.0001		
Total	1.59811	35			

Figure 159: Results of the 3 factor ANOVA test for C-CF cases (N = 504)

Order of importance of significant parameters	1	2	3	4	5
Factors	FOV	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time	FOV + driver's reaction delay

Table 49: Factor order of importance for C-CF cases (N = 504)

Cyclist Longitudinal (C-L)

Figure 160 shows the results for C-L cases. The results indicate that the three main factors intervene in the avoidance rate with the second order interaction X2*X" and X1*X3.

With consideration of the F values, the FCW trigger should be prioritized, then the driver's reaction delay, the X2*X3 and finally the FOV. Indeed due to the configuration of the scenario, the FOV parameter is less required as the cyclist is in front of the car during the scenario. Thus the effect of this parameter on the avoidance rate is strongly reduced mostly if the accident is not in a curve. The results are summarized in Table 50.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.01106	2	0.00553	67.19	0
X2	0.61845	3	0.20615	2505.17	0
X3	0.3083	2	0.15415	1873.27	0
X1*X2	0.00024	6	0.00004	0.49	0.8015
X1*X3	0.00079	4	0.0002	2.4	0.1075
X2*X3	0.21952	6	0.03659	444.6	0
Error	0.00099	12	0.00008		
Total	1.15935	35			

Figure 160: Results of the 3 factors ANOVA for C-L cases (N = 120)

Order of importance of significant parameters	1	2	3	4
Factors	FCW trigger time	Driver’s reaction delay	Driver’s reaction + FCW trigger time	FOV

Table 50: Factor order of importance for C-L cases (N = 120)

Cyclist Turning Left (C-TL)

Figure 161 shows the results of the test for P-TL cases. The results indicate that the three factors intervene in the avoidance rate as the second order interaction X2*X3.

With consideration of the F values, the FOV should be prioritized, then the driver’s reaction delay, the FCW trigger time and finally the second order interaction X2*X3. The results are summarized in Table 51.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	0.28941	2	0.14471	1488.53	0
X2	0.14181	3	0.04727	486.25	0
X3	0.17724	2	0.08862	911.61	0
X1*X2	0.00105	6	0.00018	1.81	0.18
X1*X3	0.00053	4	0.00013	1.35	0.3071
X2*X3	0.08566	6	0.01428	146.86	0
Error	0.00117	12	0.0001		
Total	0.69688	35			

Figure 161: Results of the 3 factor ANOVA test for C-TL cases (N = 280)

Order of importance of significant parameters	1	2	3	4
Factors	FOV	Driver’s reaction delay	FCW trigger time	Driver’s reaction + FCW trigger time

Table 51: Factor order of importance for C-TL cases (N = 280)

Cyclist Turning Right (C-TR)

Figure 162 shows the results of the test for the C-TR cases. The results indicate that all interactions have a significant effect on the avoidance rate.

With consideration of the F values, the FOV should be prioritized, then the driver’s reaction delay and the FCW trigger, and then the second order interaction X2*X3, X1*X3 and X1*X2. The results are summarized in Table 52.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	1.09157	2	0.54579	5024.04	0
X2	0.062	3	0.02067	190.25	0
X3	0.09407	2	0.04704	432.98	0
X1*X2	0.00204	6	0.00034	3.13	0.0438
X1*X3	0.00546	4	0.00137	12.57	0.0003
X2*X3	0.02593	6	0.00432	39.79	0
Error	0.0013	12	0.00011		
Total	1.28238	35			

Figure 162: Results of the 3 factors test for the C-TR cases (N = 492)

Order of importance of significant parameters	1	2	3	4	5	6
Factors	FOV	Driver's reaction delay	FCW trigger time	Driver's reaction + FCW trigger time	FOV + driver's reaction delay	FOV + FCW trigger time

Table 52: Factor order of importance for C-TR cases (N = 492)

General conclusion of factor influence order on cyclist cases

Table 53 summarized the results according to each scenario. It can be remarked that except for the Longitudinal scenario, the FOV parameters should be prioritized first, then the driver's reaction delay and finally the FCW trigger time. As the main factor effects have nearly always influence, it can be concluded that the avoidance rate can be greatly affected depending on the parameter settings.

Scenario/ Order	1	2	3	4	5	6	Sample size
C-CN	FOV	DR	FCW	FCW + DR	FOV + DR	-	744
C-CF	FOV	DR	FCW	FCW + DR	FOV + DR	-	504
C-L	FCW	DR	FCW + DR	FOV	-	-	120
C-TL	FOV	DR	FCW	FCW + DR	-	-	280
C-TR	FOV	DR	FCW	FCW + DR	FOV + DR	FOV + FCW	492
C-All	FOV	DR	FCW	FCW + DR	FOV + DR	-	2261

DR = Driver's reaction delay

FCW = FCW trigger time

'-': No additional significant factors

Table 53: Global view of the factor influence order on the different cyclist scenarios

4.2.3 Comparison between Pedestrian and Cyclist cases

From a global point of view, it can be observed that high benefits can be expected by the FCW either for pedestrian and cyclist cases. With the best parameter set considered in our study, i.e. FOV 70°, a FCW 2.6s and driver's reaction of 0.6s, positive effects can be obtained for 84% of pedestrian cases and 82% for cyclist cases. However, by observing Figure 138 and Figure 151, it can be observed double mitigation effect for pedestrian cases compared to cyclist for that parameter set. This difference might be explained by the difference in vehicle approach speed before the impact. As a reminder, the vehicle approach speed is the travelling speed of the vehicle prior any reaction before the impact. For pedestrians, the vehicle approach speed is 35km/h in 50% of cases and 50km/h in 80%. On the opposite for cyclists, the vehicle approach speed is 20km/h in 50% of cases and 30km/h in 80% of cases. As the same braking model is considered and due to the higher vehicle speed in pedestrian cases, this necessarily leads to more mitigation and less avoided. Indeed, the system is less effective due to the braking limitation (i.e. maximum deceleration value). It can also be recalled that the braking activation trends observed in Figure 21 and in Figure 33 are similar. Even with a higher proportion of brake activation in pedestrian cases compared to cyclists, the simulation results show an improvement through an earlier braking thanks to the FCW.

It can also be observed that a similar accident proportions are not affected by the FCW. This may results from the occlusion factor or the VRU being outside sensors FOV. Our algorithm also considers no effect when the braking initiated through the FCW happens later compared to the reaction in the original accident. Further investigations will be required to determine appropriate countermeasures to both effects which might results in detection improvement.

It can be noticed that the most challenging scenario for the pedestrian is P-CN whereas for the cyclist it is the C-TR. On the opposite, the scenarios which have the most benefit are P-CF, P-TL and C-CF.

A comparison scenario per scenario is given next.

- P-CN and C-CN: Similar positive benefits (87% for pedestrians and 88% for cyclists) can be observed. It can be highlighted that there is twice more mitigation for pedestrian cases compared to cyclist ones. This may be caused by the higher vehicle approach speed on this scenario.

- P-CF and C-CF: Similar positive benefits (95% for pedestrians and 94% for cyclists) can be observed. The higher effectiveness obtained for this scenario compared to the crossing nearside may be caused to the occlusion factors. As the VRU has to cross at least one way of road, the effect of the occlusion factor might be strongly reduced. It might be interesting to determine if the effectiveness difference is caused by this factor and if that is the case to quantify it.

- P-L and C-L: High positive benefits (94% for pedestrians and 84% for cyclists) can be obtained with higher proportion for pedestrians. It can be observed for P-L simulation results (Figure 141) that all points form a line close to the maximum effectiveness i.e. 100% positive effect by the sum of avoidance and mitigation. However due to the low sample for P-L scenario compared to C-L (20 cases versus 120), results have to be considered with caution. It might be interesting to confirm this effect with higher sample especially for the P-L scenario.

- P-TL and C-TL: Very high positive benefits can be obtained for this scenario (95% for pedestrians and 90% for cyclists) with very good avoidance rates. This very good effectiveness might come from the combination of multiple elements like the vehicle driving speed and the good visibility at the intersection. In the simulation, there is no dynamic traffic in the surrounding of the involved vehicle as there is no information relative to this element in both databases. The lack of dynamic environment may result in a better visibility and then, on a better effectiveness. In order to evaluate more accurately FCW effect on this scenario, it may be interesting to collect data of the dynamic environment either for the understanding of accident circumstances and the effectiveness evaluation.

- P-TR and C-TR: A difference can be observed in effectiveness rate when comparing pedestrian and cyclists cases. The benefits for pedestrian cases reach 94% (92% avoidance and 2% mitigation) whereas for cyclist cases the benefits reach only 79% (76% avoidance and 3% mitigation). The high difference between those scenarios may come from the combination of where the VRU comes from with his displacement speed. From the VRU relative position to the car (see Figure 31 and Figure 42) a great proportion of the VRU are coming from the right side. Due to the pedestrian low displacement speed, pedestrians are located closer to the road and car path. On contrary, due to cyclists coming from the right side and to the higher displacement speed, detecting cyclist from car point of view is much more difficult. Detecting a cyclist during a turning right manoeuver requires a much higher FOV. Additionally, the occlusion factor may also intervene due to environment infrastructure (a building reducing field of view at the intersection) and hiding the cyclist until very close to the impact. In this study, the FOV is limited to 70° (total detection cone of 140°). It might be interesting to make additional analysis with the increase of the FOV up to FOV 90° (total detection cone of 180°) in front of the vehicle. Additionally, further analysis relative to the specific effect of occlusion on avoidance may be of interest and also to quantify it. As a reminder Table 14 and Table 15 results indicate no occlusion for the design of such scenario.
When considering the four turning scenarios (P-TR, P-TL, C-TR and C-TL), it appears that the most challenging configuration for FCW concerns the C-TR.

The 3 factor ANOVA analysis on the avoidance rate shows interesting results.

When considering all pedestrian cases, there is no obvious convergence relative to which parameter to focus depending on the scenario. It should be driver's reaction for P-CN and P-L, FOV for P-TL and P-TR or the FCW trigger for P-CF scenario.

Concerning the cyclist cases, a global logic appears as it can be observed in Table 53. It indicates that the cyclist detection should be prioritized first through the FOV parameter. Then, it could be interesting to focus on reducing the driver's reaction time and finally to trigger a FCW earlier.

It can be observed a common influence on pedestrian and cyclist turning scenarios. For all those 4 scenarios, the effect on the avoidance rate is strongly affected first by the FOV, then the driver's reaction and the FCW trigger time. These results indicate that detecting the VRU should be prioritized for turning as no detection results in a no trigger of the FCW system and thus in no braking. Indeed, the cyclist detection requires a higher field of view due to cyclist higher displacement speed positioning the cyclist laterally further away from the car. On contrary, the FOV parameter has indeed less influence on pedestrian cases (at least for crossing and longitudinal scenarios) as the pedestrian can be located closer to the car's path.

4.3 Conclusion

This chapter estimates the potential safety benefit of a FCW systems based on the real-world simulation of 1509 car-to-pedestrian and 2261 car-to-cyclist accident cases. A FCW model is considered with fixed parameters and varying parameters like FCW FOV, FCW trigger time and driver's reaction delay. The accuracy of the estimated benefit is of course influenced by the FCW model (occlusion, processing time, system decision making, and so on), the driver's reaction but also highly dependent on the accident reconstruction quality. In-depth accident investigations allow reconstructing the accident pre-crash phase kinematic. However it is difficult to gather data on the dynamic surroundings such as moving vehicles that may have occluded the VRU prior the impact.

Regarding the addition of the FCW, several assumptions are made through the algorithm:

- The driver is assumed to brake along the reconstructed car trajectory and does not attempt evasive manoeuver. Consequently when applying the brake in the simulation, the car original trajectory is kept and extrapolated in time after the time zero is reached in the real accident. This assumption seems acceptable considering current knowledge on driver's reaction in evasive manoeuvers and also due to the lack of data about the dynamic environment (Hayashi et al. 2012).
- The trajectories of both car and VRU are extended linearly based on the last known segment prior the impact from the data of the original accident. For curvilinear trajectory, this hypothesis is inaccurate. However, computing the exact curvilinear trajectory based on PCM data appears complex. It requires to determine the most likely trajectory based on the infrastructure data. In the case of the end of a turning

manoeuver, the curvilinear trajectory should be changed in a rectilinear trajectory. In our simulation, the trajectories are extended for a short duration. Thus, our assumption may be suitable even if the cost is accuracy loss. A perspective should be to find and implement a method to improve the accuracy for those curvilinear trajectories and to quantify the error from our analysis.

- The brake activation depends on the FCW trigger time and also on the original accident. If brake activation in original accident is earlier than the FCW trigger time, then no effect is considered in simulation and the original kinematic is kept. It could be argued that a FCW could help to increase the force applied by the driver on the brake from the beginning of the braking. Further research could analyse if the FCW could improve driver's initial braking especially for late triggering. In the case where the driver brakes moderately before the impact, the FCW benefits are unknown.
- The brake model is simplified as an ideal braking model has been considered. A more realistic model will reduce the safety benefit observed in this study.
- The detection sensors triggering the FCW are considered as ideal as they can detect the cyclist whatever the conditions (e.g. weather like rain, fog or by sudden illumination changes).
- The detection sensor is assumed to be located in car geometrical centre whereas cameras are generally placed on the windshield at the central mirror. This should be acknowledged as increasing slightly the detection cone.
- The system algorithm is also assumed being able to predict accurately the path of the VRU to trigger appropriately the FCW. Additionally, we have not considered cases where the VRU stand still and suddenly start to move very close to the impact time. As state previously, the focus has not been done on the FCW triggering algorithm. However, this point has to be considered as avoiding collision in such situation must be challenging. It should be acknowledge that this situation will certainly lead most of the time to mitigation at best or to no effect depending on the algorithm.

Despite all these assumptions and limitations, the analysis gives some general trends for each accident scenario.

Overall results indicate that FCW potential benefits can reach up to 84% for our whole pedestrian sample with the best efficiency on Pedestrian Turning Left (P-TL) and Pedestrian Crossing Farside (P-CF) scenarios with 95% positive effects. Similarly on cyclist accidents, the positive effects can affect 82% of our whole cyclist sample with the best efficiency for Cyclist Crossing Farside (C-CF) scenario with 94% positive effects. On the opposite, the most challenging scenarios are the Pedestrian Crossing Nearside (P-CN) and the Cyclist Turning Right (C-TR). Our simulation results show optimistic results about the potential benefits of this safety device both for pedestrians and cyclists. However, further research efforts should focus on providing more evidences of this positive effect and also on other VRU. A limitation that should be kept in mind is that the current benefit estimation has been performed on accident databases and is optimistic as stated previously. It concerns only situations where the FCW activation corresponds to true positive. In order to estimate more accurately the FCW effect, an analysis on naturalistic driving data could be performed.

Additionally, the ANOVA test analysis reveals the specificities per scenario. The tests reveal the importance of each main factor effect and if a second order interaction is significant.

For pedestrian cases, if the priority is given to positively affect the higher number of accident cases, then the focus should be given to reducing driver's reaction time represented by the P-CN scenario. However, this result will be strongly dependent on the scenario accident proportions.

For cyclist cases, the result globally indicates that the focus should be given to the FOV parameter first, and then on reducing driver's reaction and finally on FCW trigger time.

For pedestrian and cyclist turning scenarios, the same hierarchical order for parameter influence has been found. In the first place, we find the FOV, then the driver's reaction and finally the FCW trigger time. The results indicate that detecting VRU in turning configurations overcomes the other two parameters (FCW trigger and driver's reaction).

To author's knowledge, this is the first study in which the potential effect of FCW is examined in turning scenarios. It can be mentioned that Lubbe and Kullgren (2015) presented a study of FCW effect on different pedestrian crossing configurations. They estimated up to 25% the potential benefit of FCW depending on the system trigger timing and the FCW signal. A comparison between Lubbe and Kullgren work and ours is not possible as their quantify benefits in terms of casualty cost contrary to our work which is on collision avoidance. Nevertheless, it appears interesting for readers to be aware of such work. AEB and FCW both aim at positively influencing road safety but less attention has been given to FCW. Many recent studies have analysed AEB benefit. The main difference between current paper and others is on the introduction of variations for the driver's reaction. Lenard et al. (2018) analysed the characteristics for an AEB and found that 90% cyclists were within a ±80° FOV (e.g. a total 160° angle) and within 50m far from the car. Thus, collisions with cyclist can be highly reduced with wider FOV. Even if our FOV parameter does not reach 80° value, it can be noticed that a 70° FOV (e.g. total FOV of 140°) and a 50m range FCW also greatly affect positively the avoidance and the mitigation rates. Zhao et al. (2019a) analysed the AEB effectiveness based on accident reconstructions from video recorder mounted on taxi vehicles. They showed that FOV parameter has a significant influence on collision avoidance. The higher is the FOV, the more accident can be avoided. They also found that with an ideal AEB system, i.e. no system braking delay and 360° detection cone, some collisions were unavoidable due to cyclists' sudden appearance in front of the car. This result is similar to the results found in this study. Collisions can be avoided at best but in some cases, the visibility criterion is so important that even mitigation is not possible when the cyclist becomes only visible very close to the car. Ohlin et al. (2017) analysed the effect of combined measures in reducing real life bicycle injuries on Swedish accidents. They found that AEB effectiveness can reach 70% for pedestrians and cyclists. Rosén (2013) also worked on cyclist AEB on 607 GIDAS-PCM cyclist cases. He also found positive effect for 55% of fatal cases and 33% of severe cases. Yue et al. (2018) also assessed the benefits of ADAS. The conclusion of their review study estimated that collision avoidance systems are limited to 70% effectiveness rate. Even if our results for FCW are optimistic, Ohlin et al. (2017), Rosén (2013) and Yue et al. (2018) results illustrate the high potential ADAS can have on road safety for bicycle.

Wu et al. (2017) examined avoidance strategies for drivers equipped with a FCW for rear-end collision. They found difference depending on the driving experience. Older drivers with more experience tend to steer if there are no car in the other lanes contrary to younger drivers who are more likely to brake to reduce accident severity. Also according to Bueno et al. (2014), FCW device is effective on low distracted drivers. However, depending on the distraction level, it can affect the visual behaviour and then braking performance (Harbluk et al. 2007). It may also play a role in the case of an unexpected event that is not perceived by the driver. One of the challenges for the FCW design might be the Human Machine Interface (HMI) to ensure a detected VRU by the car sensors is also detected by the driver. This way, FCW can help drivers to manage faster a hazardous situation if they did not anticipate the risk. However, one critical challenge for FCW design is highlighted by Dozza et al. (2017). Driver response depends on factors like visibility or time-to-arrival which is the time to arrive to a pedestrian or cyclist. Thus determining the most appropriate warning time to get the most appropriate reaction to a hazard is an important point. This is why, during the design of such system, the choice of the driver model has to be considered carefully. As shown by Bärgman et al. (2017), the choice of the driver models is of importance when considering the evaluation of a non-automatic ADAS like FCW. The driver reaction depends also on the FCW. Indeed, it appears that the type of signal (audio, video, haptic) can play an important role to reach an optimal reaction of the driver. Lylykangas et al. (2016) analyzed drivers' reaction time in emergency scenarios with FCW. They found that tactile and visual-tactile signals help drivers react faster compared to an only visual signal. Aust et al. (2013) also analyzed a combination of audio and visual signal in order to study FCW effect for repeatedly exposure on emergency braking. They found that the more drivers were exposed to FCW, the faster they can react to the signal. This is also confirmed by Koustanaï et al. (2012) where the FCW was more effective with familiarized drivers compared to unfamiliarized. Variations of driver reaction considering above parameters are considered in this paper by including a large range of driver reaction time (from 0.6 to 1.2s) but are not varied depending on driver's characteristics in our samples. Additionally, acceptance of the FCW by the driver and quicker reaction to it may depend on the balance between the number of true positive and false negative FCW trigger.

Predicting drivers' intention might be of interest. Indeed, it may reduce driver's annoyance (Diederichs et al. 2015) and maximize the effect of system activation thanks to an earlier alarm if it is identified that the driver has no awareness of the risk. Also the prediction of VRU intention is required to that effect. Meijer et al. (2017) developed an algorithm capable of cyclist intention prediction. The algorithm was able to correctly predict 94% of the cyclist intention 1s ahead. However, the further the prediction is, the more complicated is the task. Predicting pedestrian intention might be more complex comparing to cyclist as pedestrian can stop more suddenly contrary to cyclist. Thus, the elaboration of FCW systems should integrate these elements. Puente Guillen and Gohl (2019) suggested elaborating FCW system based on driver model in order to increase acceptance and then effectiveness. Also as highlighted by Jermakian (2011), system effectiveness can be limited depending on driver willingness to use these technologies. Driver comprehension and trust should be high enough in order to react appropriately to the FCW system and also to avoid turning it off.

5. Global conclusion and perspectives

5.1 Synthesis and limitations

This research aims at answering different questions relative to FCW effect on pedestrian and cyclist safety. As FCW system is supposed to trigger earlier compared to AEB system, a focus on AEB system is first needed. So, an accident analysis has been performed to determine the main issues and challenges an AEB and a FCW system can encounter. Then, a driving simulator study has been performed to extract driver's reaction to a FCW. A final part determines the potential benefits of the FCW on real-world accidents through simulation.

The analysis of accident cases allows the identification of several elements that require to be taken into account in the design of a FCW system. A literature review helps identifying and extracting five main scenarios: a crossing nearside, a crossing farside, a longitudinal, a turning left and a turning right scenario. All others cases that do not correspond to one of the five previous scenarios have been classified into an "Other" group. However, even with the identification of these scenarios, the classification of accident cases into each different scenario reveals difficulties. As no suitable classification method for our analysis has been found at the time of the accident classification work, a method has been proposed. The disadvantage of this method is that it is mainly based on visual classification criteria. The classification can then be dependent on the interpretation of the accident kinematic by the observer. However, on the other hand, it is not possible to perform an automatic classification. To perform an automatic classification, it is necessary to identify some values (like yaw rate, curvature angle, etc.) to distinguish each scenario. Even with their identifications, finding the most appropriate threshold values is challenging as it might be strongly influenced by a sample and only valid on it. Thus, applying those thresholds to another sample might lead to incorrect results.
The accident analysis allows determining general accident characteristics:

- Global accident characteristics and per scenario: like VRU relative positions to the car, VRU and car speeds. VRU are 20m far ahead the car 1s before the impact and ±3m laterally for pedestrians and ±10m for cyclists.
- The detection proportion depending on the FOV values from the car point of view. High detection rates could be obtained for pedestrians with a 40° FOV and for cyclists with a FOV 70°.
- The range value. A 45m range is sufficient to nearly detect all VRU 2s before the collision.

- The LTTB and t_{LTTB} corresponding to the minimum required distance or time to stop the vehicle in order to avoid a collision. The analysis results indicate that most t_{LTTB} are 1.5s before the collision for pedestrians and 1s for cyclists.
- The available time prior the t_{LTTB} which corresponds to the amount of time a system may have to process and trigger a safety system. Up to 70% pedestrians and cyclists can be detected 2s prior the t_{LTTB} with a FOV 70°.

The results extracted from the database analysis have been used as inputs for the driving simulation study. This study aims at determining driver's reaction to the FCW. A specific audio-visual FCW system has been used and presented to the driving simulator participants. Two hundred volunteers took part into the experiment. Some of them took part in a preliminary experiment prior the set-up of the main experiment and some others in an additional experiment. The results of the driving simulator study reveal that reproducing accident scenarios in a driving simulator is a difficult task. Indeed, an accident is a very rare event composed of three components: the infrastructure, the VRU and the vehicle i.e. the driver. Thanks to the accident analysis, recreating the infrastructure and the VRU component is possible. However, reproducing the driver component is very challenging as it needs a thorough understanding of driver's responsibility in the accident and driver's state before the collision (attention, situation risk awareness). Turning scenarios show the most variation in the driving simulator in participants' trajectories and speed. A major limitation during the data collection concerns the limitation due to the eye tracker material. The eye tracker device used is a non-mobile device which is limited in field of view. This limitation does not allow the complete analysis of driver's reaction and especially during turning manoeuvers. Additionally, an improvement of the secondary task may be of interest to reproduce circumstances leading to a collision.
General results of the driving simulator study reveal no statistical differences for the driver's reaction with or without the trigger of a FCW except for one scenario (TR-PR). The difference observed was for the gas pedal release time. Additionally, reaction time difference can be observed based on the distraction level on Longitudinal scenarios. Participants' feedbacks relative to the FCW system have been collected. Feedbacks from participants mostly indicate their personal feedback to the system. Some prefer a picture or a visual progressive indicator instead of the current word "brake" in French. Others prefer an indicator highlighting the hazard in the environment for example. Feedbacks for the audio signal are similar. Instead of the current audio beep, some people prefer a totally different audio sound but without necessarily having a proposal or a precise idea. Others express their concern relative to the perception of an audio signal and to the response to it. Additionally, they were concerned by the signal perception in a potential noisy environment (music listening, phoning and so on). Last but not least, participants' feedbacks have also been collected for the FCW trigger time. Most participants were not comfortable with the two trigger timing (1.7s and 2s) and indicate that a FCW should

trigger earlier. However, this element has to be considered with caution as some of those participants declared to react before the FCW signal which in reality was not the case. Under the hypothesis of driver potential reaction to a FCW, extracting drivers' reaction time was possible. The results indicate that the potential total duration for a driver to start initiating a braking was between 0.6s and 1.2s after a FCW signal was emitted. When the environment was more complex that interval can go from 1s to 1.6s.

Despite the fact that our experimental study did not succeed to reveal the benefit of a FCW, it was judged interesting to still evaluate the effect of a reduced driver reaction time potentially due to a FCW. Under some acceptable assumptions, different simulations have been performed using combinations of three varying parameters: the FOV, FCW trigger time and the driver's reaction. The simulation results indicate the possible positive benefits of FCW system on avoidance and mitigation on our overall sample and per scenario. 84% benefits can be expected on our total pedestrian sample and 82% on our cyclist sample. The highest effect on scenarios can be observed for P-TL and P-CF with 95% benefits and 94% for C-CF. Those results are naturally dependent on the specificities of each accident (accident scenario, participant kinematics, etc.). Also statistical analysis reveal the influence and the hierarchical order of each parameter or parameter combination on the avoidance rate depending on the scenario. It highlights that driver's reaction time should be prioritized for pedestrian safety and FOV for cyclist safety.

5.2 Perspectives

Some perspectives have been presented throughout the document. Nevertheless further additional investigations may be considered.

Our analysis has been performed on databases coming from two countries: France and Germany. Those characteristics may be only valid on the two databases where the data have been extracted. It could be interesting to make similar analysis on more databases and additionally on databases in which driving culture, driving regulations and rules are different and to compare the results. It may also be interesting to perform such analysis on database that can be representative at a national level. Indeed, EDA and PCM are not nationally representative of France and Germany. EDA is not representative due to the case number. PCM is a specific part of GIDAS and is not representative of Germany due to the selection criteria (only collision between one vehicle and one other participant). Additionally, on the last version of PCM (2018 version), the proportion difference is mentioned. For example PCM is composed of 17% pedestrian and 28% cyclist cases contrary to GIDAS where these proportions respectively represent 9% and 20% of GIDAS total sample. In order to be nationally representative of a country a method proposal could be considered. A similar analysis to what is presented in the thesis has to be performed (accident case classification, find scenario proportion with the "Others" group and so on) with a projection of benefit estimation depending on accident characteristics per scenario. As our analysis has been done on databases where only 2 participants were involved, an extrapolation method could be found by knowing those proportions at a national level. However, it should be acknowledged that accident characteristics should be similar. Otherwise, a method to extrapolate the current results should be adapted to suit the national data. This has to be combined with another method to be representative of all cases proportion involving a different participant number in accident cases (more or less than 2). This way, the data presented in this thesis might be used as a support to make more general statistic. During the different steps of this method, it will be interesting to quantify the errors and bias due to the different extrapolation methods.

Studying databases that are representative is of interest for country comparison and evaluation of the safety benefit at EU level. To extrapolate our figures to Europe, it would be necessary to sort out EU accidents under the same scenario classification which required a harmonized definition and access to further details at national/EU levels. An EU representative database would be an ideal solution.

The analysis performed during this work might help for the definition of new assessment protocol. Indeed, a Turning scenario appeared last year in EuroNCAP evaluation for only one configuration (Euro NCAP 2019b). Thus, it could be interesting to integrate other turning configurations in the evaluation.

From the new simulations integrating a FCW, the final impact speeds have been computed. In the case of mitigated cases, further analysis about the speed reduction effect might be of interest. This analysis will indicate the maximum speed effect on accident. However, effect comparisons between the difference parametric set values appear to be complex. Indeed, the proportion of mitigated cases for each scenario simulation is different and the effect might be case-dependent. Additionally, effect analysis on speed distribution would be interesting to evaluate impact of injury severity.

From the original accident kinematic, it is possible to extract the impact location of the VRU on the car front. As the new kinematic simulations integrating FCW effect has been computed, it could be interesting to determine the FCW effect on mitigated cases especially for the injuries. Indeed, depending on the impact location on the car front, FCW may reduce the injuries as it might make the injuries worse. The analysis of the combination of active and passive safety as mentioned in the chapter 1 may be of interest to quantify more precisely the FCW effect on road safety for the prediction of injuries (Hamdane et al. 2014; Lubbe 2015).

Further researches could focus more on identifying all combined elements of the human factors that lead to accidents. This might be done by gathering drivers' naturalistic data during a turning manoeuver and especially during accident circumstances. Some limitations can be found on the driving simulator study. The driving simulator used during the campaign is static and the visual appearance of the environment may be improved. Both elements might have affected the results. Also, reproducing turning accident scenarios is revealed to be a highly complex task. It may be appropriate in the first place to study more accidents in that configuration. With the help of in-depth investigations, more findings relative to the human factors will be of great help. Driver's distraction or perception of the conflict situation would guide the development of a realistic driving simulator scenario and consequently effective ADAS.

The exploitation of the main data of the driving simulator has been performed in this work. However, it might be interesting to continue the work with the consideration of the remaining data about general participant characteristics like age, gender and so on. For example, the considered population is middle-aged drivers. However, inside that class, differences might emerge depending on criteria like gender, driving experience or habits or with a finer age division group.

Avoidance and mitigation effects have been obtained for 36 combinations of those three parameters per scenario and on our whole samples. A parametric analysis has been performed in order to determine the effect of a FCW system according to different system parameters (FOV, FCW trigger time and driver's reaction). A statistical analysis has been done in order to determine the influence of each parameter on the avoidance rates and also the two or three factors interaction effects. However, finding a mathematic model that quantify precisely each effect and that fits to our 36 data per scenario and our whole samples appear to be complex and will require additional investigations.

The methodology used in this research work may be extended to other road users like powered two-wheelers or new personal mobility devices. This method may not only be centered on vehicle but it might be applied also from the VRU point of view. In that case, a warning may be given to the VRU on the oncoming danger.

Bibliography

Abe G., Richardson J., 2005, the influence of alarm timing on braking response and driver trust in low speed driving, Safety Science, vol. 43, pp. 639-654, DOI: 10.1016/j.ssci.2005.04.006.

Abe G., Richardson J., 2006, Alarm timing, trust and driver expectation for forward collision warning systems, Applied Ergonomics, vol. 37, issue 5, pp. 577-586, DOI: 10.1016/j.apergo.2005.11.001.

Aksan N., Sager L., Hacker S., Marini R., Dawson J., Anderson S., 2016, Forward Collision Warning: Clues to Optimal Timing of Advisory Warnings, SAE Int. J. Trans. Safety 4 (1), DOI: 10.4271/2016-01-1439.

Alonso M., Vega M. H., Martín O., 2012, Driving simulation study for the analysis of distraction effects in longitudinal driving behavior, Cognition, Technology & Work, vol. 14, pp. 283-297, DOI: 10.1007/s10111-011-0180-9.

Anaya J. J., Merdignac P., Shagdar O., Nashashibi F., Naranjo J. E., 2014, Vehicle to Pedestrian Communications for Protection of Vulnerable Road Users, IEEE Vehicular Technology Magazine, vol. 10, Issue 2, DOI: 10.1109/MVT.2015.2410341.

Aust M. L., Engström J., Viström M., 2013, Effects of forward collision warning and repeated event exposure on emergency braking, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 18, pp. 34-46, DOI: 10.1016/j.trf.2012.12.010.

Bagheri M., Siekkinen M., Nurminen J. K., 2014, Cellular-based vehicle to pedestrian (V2P) adaptive communication for collision avoidance, in International Conference on Connected Vehicles and Expo, Vienna, Austria, DOI: 10.1109/iccve.2014.7297588.

Bärgman J., Boda C.-N., Dozza M., 2017, Counterfactual simulations applied to SHRP2 crashes: The effect of driver behavior models on safety benefit estimations of intelligent safety systems, Accident Analysis and Prevention, vol. 102, pp. 165-180, DOI: 10.1016/j.aap.2017.03.003.

Bertozzi M., Broggi A., Felisa M., Vezzoni G., Del Rose M., 2006, Low-level Pedestrian Detection by means of Visible and Far Infra-red Tetra-vision, Intelligent Vehicles Symposium, Tokyo, Japan, pp 231-236.

Blower D., 2014, Key pedestrian collision scenarios in the U.S. for effective collision avoidance technologies, University of Michigan Transportation Research Institute, Report No. UMTRI-2014-18, USA.

Brach R.M. and Brach R.M., 2005, Vehicle Accident Analysis and Reconstruction Methods, SAE International.

Brenac T., Nachtergaële C., Reigner H., 2003, Scénarios types d'accidents impliquant des

piétons, Rapports n°256 Les collections de l'INRETS, Arcueil, France.
Bucsuházy, K., Svozilova V., Vallová O., Semela M., Sekora J., Belak M., Maxera P., Kledus R., 2016, Analysis of driver reaction time using the acquisition of biosignals, Conference ICTTE Belgrade 2016.
Bueno M., Fabrigoule C., Deleurence P., Ndiaye D., Fort A., 2012, An electrophysiological study of the impact of a Forward Collision Warning System in a simulator driving task, Brain Research, vol. 1470, pp. 69-79, DOI: 10.1016/j.brainres.2012.06.027.
Bueno M., Fabrigoule C., Ndiaye D., Fort A., 2014, Behavioural adaptation and effectiveness of Forward Collision Warning System depending on a secondary cognitive task, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 24, pp. 158-168, DOI: 10.1016/j.trf.2014.04.012.
Byatt R. and Watts R., 1981, Manual of Road Accident Investigation, Pitman.
Calvi A., Benedetto A., D'Amico F., 2015, Driver reaction time to avoid collisions during a mobile phone conversation, Proceedings of 2015 Road Safety & Simulation International Conference, Orlando, USA, pp. 690-701.
Campbell J. L., Richard C. M., Brown J. L. McCallum M., 2007, Crash warning system interfaces: Human factors insights and lessons learned, Report No HS 810 697, National Highway Traffic Safety Administration, Washington, DC.
Clabaux N., Brenac T., 2010, Scénarios types d'accidents urbains n'impliquant pas de piétons, Les collections de l'INRETS, 309p.
Coelingh E., Eidehall A., Bengtsson M., 2010, Collision Warning with Full Auto Brake and Pedestrian Detection – a practical example of Automatic Emergency Braking, 13th International IEEE Annual Conference on Intelligent Transportation Systems, Madeira Island, Portugal, pp. 155-160.
Diederichs F., Schüttke T., Spath D., 2015, Driver Intention Algorithm for Pedestrian Protection and Automated Emergency Braking Systems, in IEEE 18th International Conference on Intelligent Transportation Systems, Las Palmas, Spain, pp. 1049-1054, DOI: 10.1109/ITSC.2015.174.
Dozza M., Boda C.-N., Jaber L., Thalya P., Lubbe N., 2017, How do drivers negotiate intersections with pedestrians? Fractional factorial design in an open-source driving simulator, in Proceeding of the Road Safety and Simulation International Conference, 17-19 October 2017, Hague, the Netherlands.
Espié, S., Gauriat, P., Duraz, M., 2005, Driving simulators validation: The issue of transferability of results acquired on simulator, Driving Simulation Conference North-America (DSC-NA 2005), Orlando, FL.
Euro NCAP, 2013, Test protocol – AEB system, version 1.0, July 2013.
Euro NCAP, 2015, Test Protocol – AEB VRU systems, version 1.0.1, EUROpean New Car Assessment Program.
Euro NCAP, 2017a, Assessment protocol – pedestrian protection, version 9.0.2, November 2017
Euro NCAP, 2017b, Test protocol – AEB VRU systems, version 2.0, March 2017
Euro NCAP, 2017c, Test Protocol – AEB VRU systems, version 2.0.2, EUROpean New Car

Assessment Program.
Euro NCAP, 2018, Assessment protocol – Safety assist, version 8.0.4, November 2018
Euro NCAP, 2019a, Assessment protocol – Vulnerable road user protection, version 10.0.2, July 2019
Euro NCAP, 2019b, Test protocol – AEB VRU systems Version 3.0.2, July 2019.
European Commission, 2018, Europe on the Move: Commission completes its agenda for safe, clean and connected mobility, [online], https://ec.europa.eu/commission/presscorner/detail/en/IP_18_3708 (accessed 16-01-2020)
European Commission, 2019a, 2018 road safety statistics: what is behind the figures? [online] https://ec.europa.eu/commission/presscorner/detail/en/MEMO_19_1990 (accessed 01-16-2020)
European Commission, 2019b, Annual Accident Report 2018, [online], https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/asr2018.pdf (accessed 16-04-2020)
European Enhanced Vehicle-Safety Committee, 1998, Improved test methods to evaluate pedestrian protection afforded by passenger cars, Report, Working Group 17.
Fardi B., Dousa J., Wanielik G., Elias B., Barke A., 2006a, Obstacle Detection and Pedestrian Recognition Using A 3D PMD Camera, in Intelligent Vehicles Symposium, Tokyo, Japan, DOI: 10.1109/IVS.2006.1689632.
Fardi B., Seifert I., Wanielik G., Gayko J., 2006b, Motion-based pedestrian recognition from a moving vehicle, in Intelligent Vehicles Symposium, Tokyo, Japan, DOI: 10.1109/IVS.2006.1689631.
Ferrandez F., Brenac T., Girard Y., Lechner D., Jourdan J.-L., Nachtergaele C., Michel J.-E., 1995, L'étude détaillée d'accidents orientée vers la sécurité primaire. Méthodologie de recueil et de pré-analyse. Convention INRETS/DSCR, Presses de l'Ecole nationale des ponts et chaussées.
Fildes B., Keall M., Bos N., Lie A., Page Y., Pastor C., Pennisi L., Rizzi M., Thomas P., Tingvall C., 2015, Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes, Accident Analysis and Prevention, vol. 81, pp. 24-29, DOI: 10.1016/j.aap.2015.03.029.
Forkenbrock G., O'Harra B., 2009, A Forward Collision Warning (FCW) Performance Evaluation, Proceedings of the 21st (ESV) International Technical Conference on the Enhanced Safety of Vehicles, Stuttgart, Germany.
Forkenbrock G., Snyder A., Heitz M., Hoover R. L. D., O'Harra B., Vasko S., Smith L., 2011, A Test Track Protocol for Assessing Forward Collision Warning Driver-Vehicle Interface Effectiveness, National Highway Traffic Safety Administration, Report No DOT HS 811 501, p. 143.
Fredriksson R. and Rosén E., 2012, Integrated pedestrian countermeasures – Potential of head injury reduction combining passive and active countermeasures, Safety Science, vol. 50, Issue 3, pp. 400-407, DOI: 10.1016/j.ssci.2011.09.019.
Fritsche P., Zeise B., Hemme P., Wagner B., 2017, Fusion of Radar, LiDAR and Thermal

Information for Hazard Detection in Low Visibility Environments, in IEEE International Symposium on Safety, Security and Rescue Robotics, Shanghai, China, DOI: 10.1109/SSRR.2017.8088146.
Fuerstenberg K. and Willhoeft V., 2001, Object Tracking and Classification using Laserscanners – Pedestrian Recognition in urban environment, in IEEE Intelligent Transportation Systems Conference Proceedings, Oakland, USA, DOI: 10.1109/ITSC.2001.948699.
Gandhi T., Trivedi M. M., 2007, Pedestrian Protection Systems: Issues, Survey, and Challenges, IEEE Transactions on Intelligent Transportation Systems, vol. 8, no. 3, pp. 413-430, DOI: 10.1109/TITS.2007.903444.
Gavrila D.M., Giebel J., Munder S., 2004, Vision-Based Pedestrian Detection: The PROTECTOR System, IEEE Intelligent Vehicles Symposium, Parma, Italy.
Geronimo D., López A. M., Sappa A. D., Graf T., 2010, Survey of Pedestrian Detection for Advanced Driver Assistance Systems, IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 32, no. 7, pp. 1239-1258, DOI: 10.1109/TPAMI.2009.122.
GIDAS, 2020, URL https://www.gidas.org/en/about-gidas/gidas-methodik/ (accessed August 2018)
Guillaume A., Hermitte T., Hervé V., Fricheteau R., 2015, Car or ground: which causes more pedestrian injuries?, Proceedings of the International Technical Conference on the Enhanced Safety of Vehicles, Paper 15-0084, Gothenburg, Sweden.
Hamdane H., Anderson R., Masson C., Llari M., Serre T., 2014, Assessment methodology of Active Pedestrian Safety Systems: an estimation of safety impact, Proceedings of the 3rd SIMBIO-M conference, 19-20 June 2014, Marseille, France.
Hamdane H., Serre T., Masson C., Anderson R., 2015, Issues and challenges for pedestrian active safety systems based on real world accidents, Accident Analysis and Prevention, vol. 82, pp. 53-60.
Hamdane H., Serre T., Masson C., Anderson R., 2016, Relevant factors for active pedestrian safety based on 100 real accident reconstructions, International Journal of Crashworthiness, vol. 21, pp. 51-62, DOI: 10.1080/13588265.2015.1113618.
Haque Md. M., Washington S., 2013, Stopping behaviour of drivers distracted by mobile phone conversations, Australasian Transport Research Forum 2013 Proceedings, 2-4 October 2013, Brisbane, Australia.
Harbluk J. L., Noy Y. I., Trbovich P. L., Eizenman M., 2007, An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance, Accident Analysis and Prevention, vol. 39, pp. 372-379, DOI: 10.1016/j.aap.2006.08.013.
Hayashi R., Isogai J., Raksincharoensak P., Nagai M., 2012, Autonomous collision avoidance system by combined control of steering and braking using geometrically optimized vehicular trajectory, Vehicle System Dynamics, 50:sup1, 151-168, DOI: 10.1080/00423114.2012.672748.
Holding P. N., Chinn B. P., Happian-Smith J., 2001, Pedestrian protection – An evaluation

of an airbag system through modelling and testing, in International Technical Conference on Enhanced Safety of Vehicles, Paper 2001-06-04, Amsterdam, The Netherlands.

Høye A., Hesjevoll I. S., Vaa T., 2015, Advanced driver assistance systems – status and future potential, TØI Report 1450/2015, Oslo 162 pages.

Huang S. N., Yang J. K., Eklund F., 2006, Analysis of Car-Pedestrian Impact Scenarios for the Evaluation of a Pedestrian Sensor System Based on the Accident Data from Sweden, International Conference on Expert Symposium on Accident Research, Hannover, Germany, pp. 136-143.

Huang S., Yang J., Eklund F., 2008, Evaluation of remote pedestrian sensor system based on the analysis of car-pedestrian accident scenarios, Safety Science, vol. 46, pp.1345-1355, DOI: 10.1016/j.ssci.2007.08.004.

Hunter W. W., Pein W. E., Stutts J. C., 1997a, Bicycle crash types: a 1990's informational guide, Report No. FHWA-RD-96-104, 116 pages.

Hunter W. W., Stutts J. C., Pein W. E., 1997b, Pedestrian crash types: a 1990's informational guide, Report No. FHWA-RD-96-163, 99 pages.

Hussain Q., Feng H., Grzebieta R., Brijs T., Olivier J., 2019, The relationship between impact speed and the probability of pedestrian fatality during a vehicle-pedestrian crash: A systematic review and meta-analysis, Accident Analysis and Prevention, vol. 129, pp. 241-249, DOI: 10.1016/j.aap.2019.05.033.

Hussein A., Garcia F., Armingol J. M., Olaverri-Monreal C., 2016, P2V and V2P communication for Pedestrian warning on the basis of Autonomous Vehicles, in 2016 IEEE 19th International Conference on Intelligent Transportation Systems, Rio de Janeiro, Brazil, DOI: 10.1109/itsc.2016.7795885.

Jeon W., Rajamani R., 2018, A Novel Collision Avoidance System for a Bicycle, Report No CTS 18-06.

Jeppsson H., Östling, M. Lubbe N., 2018, Real life safety benefits of increasing brake deceleration in car-to-pedestrian accidents: Simulation of Vacuum Emergency Braking, Accident Analysis and Prevention, vol. 111, pp. 311-320.

Jermakian J. S., 2011, Crash avoidance potential of four passenger vehicle technologies, Accident Analysis and Prevention, vol. 43, pp. 732-740, DOI: 10.1016/j.aap.2010.10.020.

Jermakian J. S., Zuby D. S., 2011, Primary Pedestrian Crash Scenarios: Factors Relevant to the Design of Pedestrian Detection Systems, Insurance Institute for Highway Safety, Arlington, USA.

Johansson G., Rumar, K., 1971, Drivers' brake reaction times, Human Factors, vol. 13, Issue 1, pp 23-27, DOI: 10.1177/001872087201300104.

Kaida K., Takahashi M., Åkerstedt T., Nakata A., Otsuka Y., Haratani T., Fukasawa K., 2006, Validation of the Karolinska sleepiness scale against performance and EEG variables, Clinical Neurophysiology, vol. 117, Issue 7, pp. 1574-1581, DOI: 10.1016/j.clinph.2006.03.011.

Keall M., D'Elia A., Newstead S., Watson L., 2014, Retrospective and projected future impact of characteristics of the New Zealand and Australian vehicle fleet on pedestrian injury, Monash University Accident Research Centre, Report No. 320, Australia.

Koustanaï A., Cavallo V., Delhomme P., Mas A., 2012, Simulator Training With a Forward Collision Warning System : Effects on Driver-System Interactions and Driver Trust, Human Factors : The Journal of the Human Factors and Ergonomics Society, vol. 54, No 5, pp. 709-721, DOI: 10.1177/0018720812441796.

Kuehn, M., Hummel T., Lang A., 2015, Cyclist-car accidents – Their consequences for cyclists and typical accidents scenarios, Proceedings of the 24th International Conference on the Enhanced Safety of Vehicles, Gothenburg, Sweden, paper number 15-0243.

Kusano K. D. and Gabler H. C., 2012, Safety Benefits of Forward Collision Warning, Brake Assist, and Autonomous Braking Systems in Rear-End Collisions, IEEE Transactions on Intelligent Transportation Systems, vol. 13, No. 4, pp. 1546-1555, DOI: 10.1109/TITS.2012.2191542.World Health Organization, 2018, Global status report on road safety, Geneva, Switzerland.

Lara A., Skvarce J., Feifel H., Wagner M., Tengeiji T., 2019, Harmonized pre-crash scenarios for reaching global vision zero, in 26th International Technical Conference on the Enhanced Safety of Vehicles, Paper Number 19-0110, p. 19, Eindhoven, Netherlands.

Lechner D., Malaterre G., Fleury D., 1986, La reconstitution cinématique des accidents, rapport INRETS n°21.

Lechner D. and Ferrandez F., 1990, Analysis and reconstruction of accident sequences, XXIII FISITA Congress, ATA, Torino, Italy, pp. 931-939.

Lenard J., Welsh R., Danton R., 2018, Time-to-collision analysis of pedestrian and pedal-cycle accidents for the development of autonomous emergency braking systems, Accident Analysis and Prevention, vol. 115, pp. 128-136, DOI: 10.1016/j.aap.2018.02.028.

Li X., Flohr F., Yang Y., Xiong H., Braun M., Pan S., Li K., Gavrila D. M., 2016, A New Benchmark for Vision-Based Cyclist Detection, Proceedings IEEE Intelligent Vehicles Symposium (IV), Gothenburg, Sweden, DOI: 10.1109/IVS.2016.7535515.

Lim J-H., Park J-S., Yun Y-W., 2014, Design of an airbag system of a mid-sized automobile for pedestrian protection, in Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 229, Issue 5, pp. 656-669, DOI: 10.1177/0954407014551186.

Lubbe N., 2015, Integrated pedestrian safety assessment: a method to evaluate combinations of active and passive safety.

Lubbe N., Kullgren A., 2015, Assessment of Integrated Pedestrian Protection Systems with Forward Collision Warning and Automated Emergency Braking, Proceedings of International Research Council on the Biomechanics of Injury, Paper IRC-15-51, pp. 385-397, Lyon, France.

Lubbe N., Jeppsson H., Ranjbar A., Fredriksson J., Bärgman J., Östling M., 2018, Predicted

road traffic fatalities in Germany: the potential and limitations of vehicle safety technologies from passive safety to highly automated driving, IRCOBI conference, IRC-18-11, p. 36, Athens, Greece.
Lylykangas J., Surakka V., Salminen K., Farooq A., Raisamo R., 2016, Responses to visual, tactile and visual-tactile forward collision warnings while gaze on and off the road, vol. 40, pp. 68-77, DOI: 10.1016/j.trf.2016.04.010.
MacAlister A., Zuby David S., 2015, Cyclist crash scenarios and factors relevant to the design of cyclist detections systems, International Research Council on Biomechanics of Injury Conference. Lyon, France, pp. 373-384.
Maki T., Asai T., Kajzer J., 2003 Development of future pedestrian protection technologies, Proceeding of the 18th International Technical Conference on the Enhanced Safety of Vehicles, Paper Number 165, Nagoya, Japan.
Makishita H., Matsunaga K., 2008, Differences of drivers' reaction times according to age and mental workload, Accident Analysis and Prevention, vol. 40, Issue 2, pp. 567-575, DOI: 10.1016/j.aap.2007.08.012.
Martin J.-L., Wu D., 2015, Accidentologie des piétons, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR) (Livrable 4.4), France.
Martinez-Ruiz V., Jiménez-Mejías E., Amezcua-Prieto C., Olmedo-Requena R., Dios Luna-del-Castillo J., Lardelli-Claret P., 2015, Contribution of exposure, risk of crash and fatality to explain age- and sex-related differences in traffic-related cyclist mortality rates, Accident Analysis and Prevention, vol. 76, pp. 152-158, DOI: 10.1016/j.aap.2015.01.008.
Masson C., Serre T., Cesari D., 2009, Pedestrian-vehicle accident: analysis of 4 full scale tests with PHMS, 20th International Technical Conference on the Enhanced Safety of Vehicles, Paper 07-0428, Lyon, France.
Matlab, 2012, The MathWorks Inc.
Mehler B., Reimer B., Dusek J. A., 2011, MIT AgeLab Delayed Digit Recall Task, Working Paper 2011-3B.
Meijer R., de Hair S., Elfring J., Paardekooper J.P., 2017, Predicting the intention of cyclists, 6th Annual International Cycling Safety Conference, Davis, California, USA.
Meinecke M.-M., Obojski M. A., Töns M., Dehesa M., 2005, SAVE-U: First experiences with a pre-crash system for enhancing pedestrian safety, in 5th European Congress and Exhibition on Intelligent Transport Systems.
Merat N., Kountouriotis G., Tomlinson A., Carsten O., Engström J., 2015, Performance on the Detection Response Task during driving: Separating the manual and cognitive element of the secondary task, in 4th International Driver Distraction and inattention Conference, Sydney, Australia.
Mukhtar A., Xia L., Tang T.B., 2015, Vehicle detection techniques for collision avoidance systems: A review, IEEE Transactions on Intelligent Transportation Systems, vol. 16, no 5, pp. 2318-2338, DOI: 10.1109/TITS.2015.2409109.
Nie J., Li G., Yang J., 2015, A Study of Fatality Risk and Head Dynamic Response of Cyclist

and Pedestrian Based on Passenger Car Accident Data Analysis and Simulations, Traffic Injury Prevention, vol. 16 pp. 76-83, DOI: 10.1080/15389588.2014.881477.
Ohlin M., Strandroth J., Tingvall C., 2017, The combined effect of vehicle frontal design, speed reduction, autonomous emergency braking and helmet use in reducing real life bicycle injuries, Safety Science, vol. 92, pp. 338-344, DOI: 10.1016/j.ssci.2016.05.007.
Op den Camp O., van Montfort S., Uittenbogaard J., 2016, CATS Deliverable 6.1: CATS Final project summary report, TNO 2016 R10921.
Puente Guillen P., Gohl I., 2019, Forward collision warning based on a driver model to increase drivers' acceptance, Traffic Injury Prevention, 20:sup1, S21-S26, DOI: 10.1080/15389588.2019.1623397.
Rahimian P., O'Neal E. E., Zhou S., Plumbert J. M., Kearney J. K., 2018, Harnessing Vehicle-to-Pedestrian (V2P) Communication Technology: Sending Traffic Warnings to Texting Pedestrians, Human Factors: The Journal of the Human Factors and Ergonomics Society, vol. 60, Issue 6, pp. 833-843, DOI: 10.1177/0018720818781365.
Ranjbar, 2014, Active Safety for Car-to-Bicyclist Accidents, Master thesis, Gothenburg, Chalmers University of Technology, Sweden.
Reynolds C C., Harris M. A., Teschke K., Cription P. A., Winters M., 2009, The Impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature, Environmental Health, vol. 8, pp.47, DOI: 10.1186/1476-069X-8-47.
Robartes E., Chen T. D., 2017, The effect of crash characteristics on cyclist injuries: An analysis of Virginia automobile-bicycle crash data, vol. 104, pp. 165-173, DOI: 10.1016/j.aap.2017.04.020.
Rodarius C., Kwakkernaat M., Edwards M., de Hair S., Pla M., 2014, Benefit estimate based on previous studies for pre-crash bicyclist systems and recommendations for necessary changes to pedestrian test and assessment protocol (No. AsPeCSS D1.5)
Rosén E., Sander U., 2009, Pedestrian fatality risk as a function of car impact speed, Accident Analysis and Prevention, vol. 41, pp. 536-542, DOI: 10.1016/j.aap.2009.02.002.
Rosén E., Källhammer J.-E., Eriksson D., Nentwich M., Fredriksson R., Smith K., 2010, Pedestrian injury mitigation by autonomous braking, Accident Analysis and Prevention, vol. 42, pp. 1949-1957, DOI: 10.1016/j.aap.2010.05.018.
Rosén E., Stigson H., Sander U., 2011, Literature review of pedestrian fatality risk as a function of car impact speed, Accident Analysis and Prevention, vol. 43, pp. 25-33, DOI: 10.1016/j.aap.2010.04.003.
Rosén E., 2013, Autonomous Emergency Braking for Vulnerable Road Users, Proceedings of International Research Council on the Biomechanics of Injury, Gothenburg, Sweden, pp. 618-627.
Saadé J., Chajmowicz H., Cuny S., 2019, Prospective Evaluation of the Effectiveness of

Autonomous Emergency Braking Systems in Increasing Pedestrian Road Safety in France, Proceedings of International research Council on the Biomechanics of Injury, 12 p., Florence, Italy.
Schaller T., Aparicio A., Gruber C., Pla M., 2012, Report describing the comparative survey of existing test protocols and test facilities (No. AsPeCSS D2.2).
Scheunert U., Cramer H., Fardi B., Wanielik G., 2004, Multi Sensor based Tracking of Pedestrians : A Survey of Suitable Movement Models, IEEE Intelligent Vehicles Symposium, Parma, Italy, pp. 774-778.
Schleinitz K., Petzoldt T., Franke-Bartholdt L., Krems J., Gehlert T., 2017, The German Naturalistic Cycling Study – Comparing cycling speed of riders of different e-bikes and conventional bicycles, Safety Science, vol. 92, pp. 290-297, DOI: 10.1016/j.ssci.2015.07.027.
Schubert A., Erbsmehl C., Hannawald L., 2012, Standardized Pre-Crash-Scenarios in digital format on the basis of the VUFO simulation, Proceedings of ESAR Conference, Stuttgart, Germany.
Schweitzer N., Apter Y., Ben-David G., Liebermann D. G., Parush A., 1995, A field study on braking responses during driving. II. Minimum driver braking times, Ergonomics, vol. 38, Issue 9, pp. 1903-1910, DOI: 10.1080/00140139508925238.
Seacrist T., Douglas E. C., Graci V., Loeb H. S., 2019, Evaluation of AEB effectiveness using counterfactual simulations of SHRP2 naturalistic crashes, 26th International Technical Conference on the Enhanced Safety of Vehicles, Paper 19-0213, Eindhoven, Netherlands
Seeing Machines, 2020, [online], https://www.seeingmachines.com/ (accessed 27-04-2020)
Serre T., 2009, Quels moyens de protection pour le piéton en sécurité passive, in Colloque francophone international de la Plate-forme intégratrice Comportement du piéton dans son environnement, Lyon, France, les collections de l'INRETS.
Snedecor G. W., Cochran W. G., 1989, Statistical methods, 8th edition Ames: Iowa State University Press.
Strayer D. L., Cooper J. M., Turrill J., Coleman J., Medeiros-Ward N., Biondi F., 2013, Measuring Cognitive Distraction in the Automobile, Washington D.C.
Szarvas M., Sakai U., Ogata J; 2006 Real-time Pedestrian Detection Using LIDAR and Convolution Neural Networks, Proceedings IEEE Intelligent Vehicles Symposium, pp. 213-218, Tokyo, Japan.
Tefft B. C., 2013, Impact speed and a pedestrian's risk of severe injury or death, Accident Analysis and Prevention, vol. 50, pp. 871-878, DOI: 10.1016/j.aap.2012.07.022.
Turner M. L., Engle R. W., 1989, Is Working Memory Capacity Task Dependent?, Journal of memory and language, vol. 28, Issue 2, pp. 127-154, DOI: 10.1016/0749-596X(89)90040-5.
Uittenbogaard J., Rodarius C., Op den Camp O., 2016a, CATS car-to-cyclist accident scenarios, TNO 2014 R11594 (CATS Deliverable 1.2).
Uittenbogaard J., Op den Camp O., van Montfort S., 2016b, CATS car-to-cyclist accident

parameters and test scenarios, TNO 2014 R11705 (CATS Deliverable 2.2)
Van Brummelen J., Emran B., Yesilcimen K., Najjaran H., 2016, Reliable and Low-cost Cyclist Collision Warning System for Safer Commute on Urban Roads, in IEEE International Conference on Systems, Man, and Cybernetics, Budapest, Hungary, DOI: 10.1109/smc.2016.7844814.
Vandenbulcke G., Thomas I., Panis L. I., 2014, Predicting cycling accident risk in Brussels: A spatial case-control approach, Accident Analysis and Prevention, vol. 62, pp. 341-357, DOI: 10.1016/j.aap.2013.07.001.
Van der Hulst M., Meijman T., Rothengatter T., 1999, Anticipation and the adaptive control of safety margins in driving, Ergonomics, vol. 42, No. 2, pp. 336-345, DOI: 10.1080/001401399185694.
Violette E. and Le Bec P.J., 2016, Freinage d'urgence motos vs voitures particulières, Essais sur piste, CEREMA, Rapport.
VUFO GmbH (Institute for Traffic Accident Research at Dresden University of Technology), 2016, Codebook GIDAS based Pre-Crash-Matrix® (PCM), Version 4.0 2016-1, August 2016, Dresden, Germany.
VUFO GmbH (Institute for Traffic Accident Research at Dresden University of Technology), 2016b, Codebook GIDAS – belongs to the database 161231_GIDAS2016, Dresden, Germany,
Wang J., Huang H., Zeng Q., 2017, The effect of zonal factors in estimating crash risks by transportation modes: Motor vehicle, bicycle, and pedestrian, Accident Analysis and Prevention, vol. 98, pp. 223-231, DOI: 10.1016/j.aap.2016.10.018.
Warshawsky-Livne L., Shinar D., 2002, Effects of uncertainty, transmission type, driver age and gender on brake reaction and movement time, Journal of Safety Research, vol. 33, pp. 117-128, DOI: 10.1016/S0022-4375(02)00006-3.
Wisch M., Lerner M., Schneider A., Juhász J., Attila G., Kovaceva J., Bálint A., Lindman M., 2016, Accident Analysis, Naturalistic Observations and Project Implications – Part A: Accident data analyses, European Commission, (Prospect Deliverable D2.1).
Wood J., Zhang S., 2017, Evaluating Relationships Between Perception-Reaction Times, Emergency Deceleration Rates, and Crash Outcomes Using Naturalistic Driving Data, Mountain-Plains Consortium 17-338.
Wolfermann A., Alhajyaseen W. K. M., Nakamura H., 2011, Modeling Speed Profiles of Turning Vehicles at Signalized Intersections, in 3rd International Conference on Road Safety and Simulation, Indianapolis, USA.
Wu X., Miucic R., Yang S., Al-Stouhi S., Misener J., Bai S., Chan W., 2014, Cars Talk to Phones: A DSRC Based Vehicle-Pedestrian Safety System, In IEEE 80th Vehicular Technology Conference (VTC2014-Fall), Vancouver, Canada, DOI: 10.1109/vtcfall.2014.6965898.
Wu X., Boyle L. N., Marshall D., 2017, Drivers' avoidance strategies when using a Forward Collision Warning (FCW) system, Proceedings of the Human Factors and Ergonomics Society 2017 Annual Meeting, vol. 61, no 1, pp. 1939-1943, DOI: 10.1177/1541931213601964.

Yang H-I., Yun Y-W., Park G-J., 2015, Design of pedestrian protection airbag system using experiments, in Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 230, Issue 9, pp. 1182-1195, DOI: 10.1177/0954407015603854.

Yue L., Abdel-Aty M., Wu Y., Wang L., 2018, Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low level automation systems, Accident Analysis and Prevention, vol. 117, pp. 55-64, DOI: 10.1016/j.aap.2018.04.002.

Young M. S., Stanton N. A., 2007, Back to the future: Brake reaction times for manual and automated vehicles, Ergonomics, vol. 50, No 1, pp. 46-58, DOI: 10.1080/00140130600980789.

Zador P. L., Krawchunk S. A., Vaos R. B., 2000, Automotive Collision Avoidance (ACAS) Program: Final report, Washington DC, National Highway Traffic Safety Administration.

Zhao Z., Zhou L., Zhu Q., Luo Y., Li K., 2017, A review of essential technologies for collision avoidance assistance systems, Advances in Mechanical Engineering, vol. 9(10), DOI: 10.1177/1687814017725246.

Zhao Y., Ito D., Mizuno K., 2019a, AEB effectiveness evaluation based on car-to-cyclist accident reconstructions using video of driver recorder, Traffic Injury Prevention, vol. 20, no 1, pp. 100-106, DOI: 10.1080/15389588.2018.1533247.

Zhao Y., Ito D., Mizuno K., Kong C., 2019b, AEB effective evaluations by accident reconstructions using videos of drive recorders in perpendicular and turning car-to-cyclist collisions, Proceedings of International research Council on the Biomechanics of Injury, p. 13, Florence, Italy.

Appendix

A. Driving simulator preliminary test

Objectives of the test

- Evaluate the experimental set-up
- Set-up of the analysis result method
- Effect of the scenario order

Sample

A sample of 20 participants has been selected. The selection criteria are listed below:

- 25-55 years-old (middle-aged)
- Non-professional drivers
- At least 3 years of driving experience

Experimental protocol

All participants were briefed on task requirements by the experimenter. They were asked to complete some questionnaires in French: global information about drivers, Karolinska Sleepiness Scale, Big 5 Personality Scale and BIS-BAS questions. Each participant was then given 10 minutes practical drive to familiarize themselves with the driving simulator. The familiarization scenario is described below. Participants were then asked to fill Stress and Arousal Checklist and Perceived Stress Scale (PSS). After that, the experimental trials were started with the Pedestrian Crossing Nearside (P-CN) scenario and the Cyclist Longitudinal (C-L) scenario. For each scenario, participants were asked to follow a precise direction at maximum authorized speed. Moreover, if participants were driving too slowly i.e. below 45kph, they were reminded verbally by the experimenter to drive at the maximum authorized speed. Between each scenario experimented, there was a 5-min break. Finally, participants were asked to fill in a form about their opinion on the experimented scenario and again a Karolinska Sleepiness Scale. Scenario order was randomized and counterbalanced for participants. After the completion of the last questionnaire part, a debriefing explaining in detailed the aims of the study was done allowing participants to have some rest before leaving.

Data about the questionnaire others than general information have not been processed.

The experiment sequence for one person is as below:

- Welcome and experiment briefing (5 min)
- Fill global information, KSS, Big 5 Personality Scale questionnaire (25 min)
- Eye tracker calibration (5 min)
- Driving simulator familiarization (10 min)
- Fill Stress and Arousal Checklist and PSS (8min)
- Scenario 1 (5 min)
- Break (5 min)
- Scenario 2 (5 min)
- Fill last part of questionnaire (8 min)

- Rest and debriefing (10 min)

Total estimation duration: about 1h30 in average.

Scenario description

Familiarization scenario

After being installed in the driving simulator, participants were asked to follow a precise direction indicated by traffic sign. In front of participant's car there was a lead car that participants cannot overtake as instructed by the experimenter. The lead car drove at different speed i.e. the lead car may quickly decelerate to drive slower obliging driver to decelerate too. For a long straight road, there is a lead car but after the first turn, the lead car is no present until the end of the scenario. The duration for this part is 10 to 15 minutes. The aims of this scenario is for participants to get acquainted with the simulator and to its braking system.

Pedestrian Crossing Nearside

Participants were asked to follow a precise direction indicated by traffic sign, thus participants drove down in straight direction during the whole scenario. The road is a 2 way road. Each road has a lateral size of 3m. The origin of the lateral axis is the center of the 2 way road. To avoid participants to drive too fast a speed limiter that limit car to 54kph was added.

The Pedestrian is located 4.5 meters in lateral according to the center of the road and visually appears behind the bus station. The pedestrian begins to walk 2.5s before the potential impact position which is expected at a lateral distance of 1.5m to the center of the road as indicated in the Figure 1. The trigger of the Pedestrian is based on vehicle instant speed. It begins 2.5s before that the center of the vehicle arrives to the position of the center of the Pedestrian. In this way the Pedestrian trigger time remains the same whatever vehicle speed. The Pedestrian walks at a speed of 1.3m/s (5kph). The pedestrian becomes visible only at a lateral distance of 3.33m (TTC 1.4s) according the center of the road.

Remark: this was a mistake in the test set-up as pedestrian visibility was expected at TTC 2.5s. This will have to be considered in the analysis of the results.

There is traffic coming from the opposite road until 500m before arriving to the position of the bus stop/pedestrian. Less than 500m before the bus stop, there is no traffic to the critical moment when the Pedestrian crosses the road, there is no moving object or person in participant's field of view.

The scenario ends when the message 'End' ('Terminé' in French) is displayed on the screen.

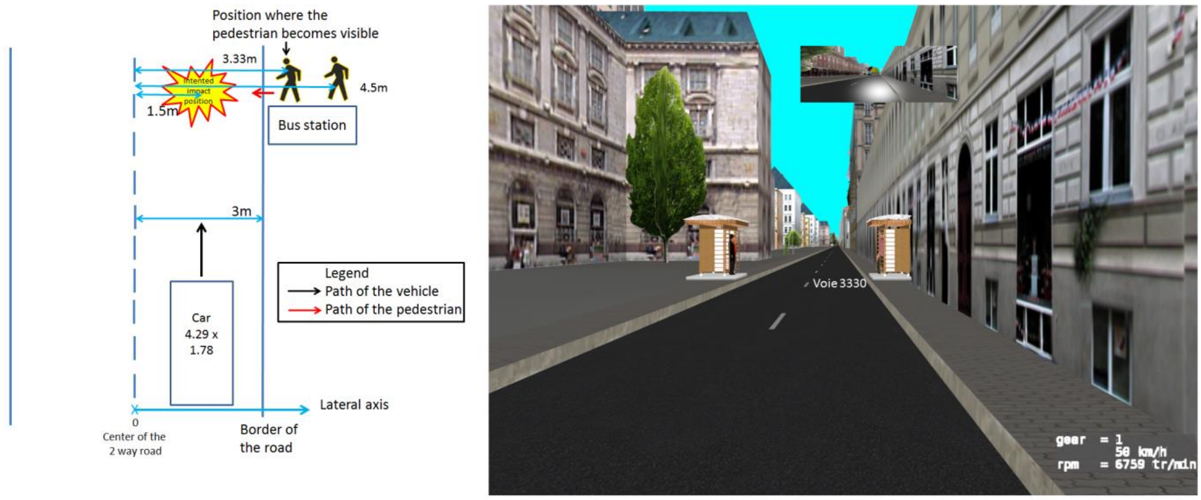


Figure 1: pattern of the Pedestrian Crossing Nearside scenario on the left side of the figure. The trigger of the Pedestrian is based on vehicle instant speed 2.5s before the vehicle center arrives to the position of the Pedestrian. On the right side of the figure, the lateral position from where the Pedestrian becomes visible.

Cyclist Longitudinal

Participants were asked to follow a specific direction indicated by traffic sign. They have a portion of the scenario on a straight road until they reach a traffic light which always turns red to force drivers to stop. At this traffic light they turn to the right to begin the configuration of the Longitudinal scenario. During the whole scenario, the road is a 2 way road. The origin of the lateral axis is the center of the 2 way road.

The Cyclist is located on the right side of the road at a lateral distance of 2.2m to the center of the 2 way road and his speed is 5.007m/s (18kph). The Cyclist always stays at a lateral distance of 2.2m during the entire scenario.

There is traffic coming from the opposite road with a short break to allow participants to overtake the Cyclist.

The scenario ends when the message ‘End’ (‘Terminé’ in French) is displayed on the screen.

See Figure 2 for a pattern of the Longitudinal configuration.

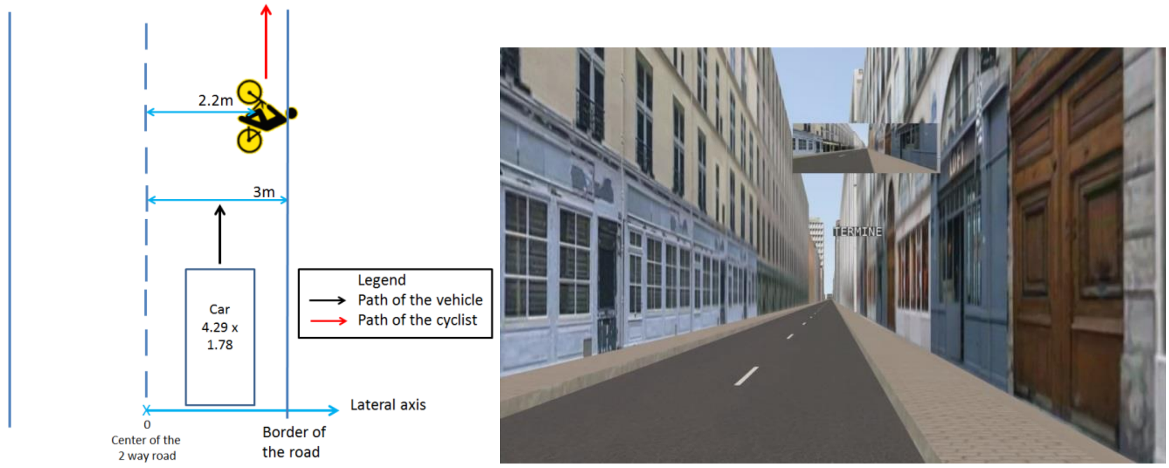


Figure 2: pattern of the Cyclist Longitudinal scenario on the left side of the figure. On the right side of the figure, the end sequence message ‘Terminé’ is displayed.

Variables analyzed

Pedestrian Crossing Nearside

Here is a list of all variables analyzed for the Pedestrian Crossing Nearside scenario:

- The time to release the gas pedal
- The time to begin to push the brake pedal
- The number of accidents and the collision speed when the vehicle impacts the Pedestrian
- Participants’ manoeuvers
- Participants’ gaze location
- Gas and brake pedal stroke

A description is given above about the method used to obtain each result.

Time to release the gas pedal

The origin of the calculation of braking time is as follow: we consider the beginning of the time at the moment where the pedestrian is visible. From here, the timer starts and stops when the driver completely releases the gas pedal i.e. the gas pedal is at its initial position at the beginning of the driving simulation (see Figure 3).

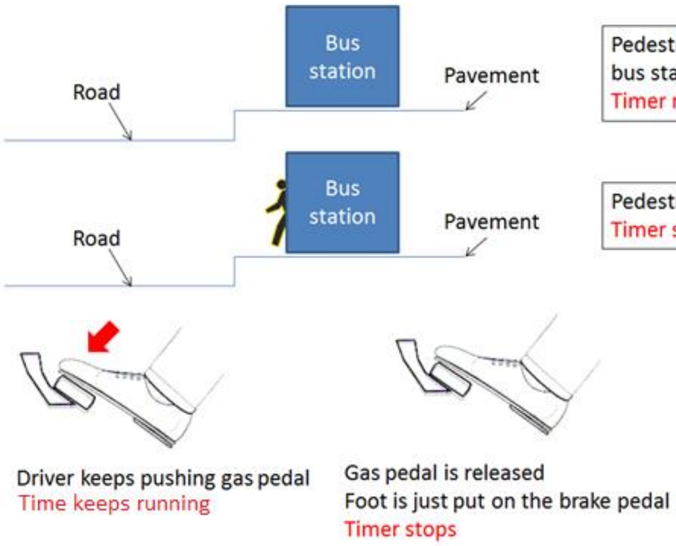


Figure 3: how the time to release the gas pedal is calculated

On driving simulator files, we consider t=0s when the pedestrian becomes visible i.e. when his lateral position is 3.33m to the center of the 2 way road in driving simulator file). We consider that the gas pedal is released or not pushed when the value of gas pedal stroke is 0, otherwise for any other positive value, gas pedal is depressed. When the value of gas pedal stroke reaches 0, we take the associate GMT time and we subtract to this value the GMT time when the pedestrian becomes visible to obtain the time to release the gas pedal. In some cases, the gas pedal has already been released by participants, and then we do not take into account those participants in the analysis for the gas pedal release time.

Time to begin to push the brake pedal

The origin of the calculation of this value is done as follow: we consider the beginning of the sequence when the pedestrian is visible from behind the bus station. From here the timer stops when drivers start to push the brake pedal (see Figure 4).

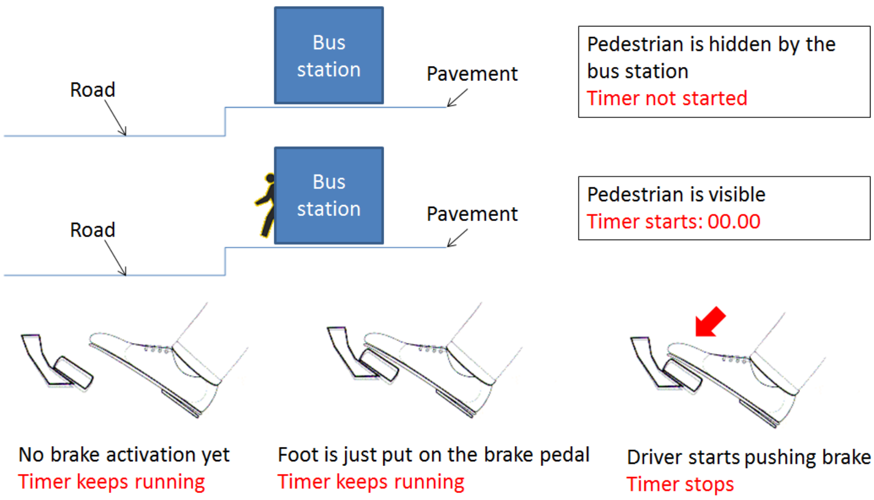


Figure 4: how the time to release the gas pedal and start to brake is calculated

On driving simulator files, we consider t=0s when the pedestrian becomes visible as explained previously when his lateral position is 3.33m to the center of the 2 way road. We consider that participants begin to start to brake when the brake pedal stroke is depressed i.e. when the value of the brake pedal stroke is strictly positive. That means that as long as the brake pedal stroke value stays at 0, the timer keeps running. When the brake pedal value is no longer 0, we take the associate GMT time and we subtract the GMT time when the pedestrian becomes visible. Thus, we have the time participants take to start to brake. A filtering is applied in order to avoid noise effect on data.

Number of accidents and collision speed

To determine if an accident occurs, we proceed as follow. We have the coordinates of the center of the vehicle and the coordinates of the pedestrian. The pedestrian is considered as a single point given by his coordinates. From this, at each time step, we compute the area between the center of the vehicle to the lead end in front of the vehicle using the following dimensions: in our study, we consider that the vehicle size is 4.29m length and 1.78m width. So at each moment, we have the front area of the vehicle and we can determine if the pedestrian is inside this area. If it is, we then consider that an accident occurs, otherwise the participant avoids the accident. If an accident occurs, we get the instant speed value when the collision happens. Figure 5 illustrates cases when accident is avoided and when an accident occurs.

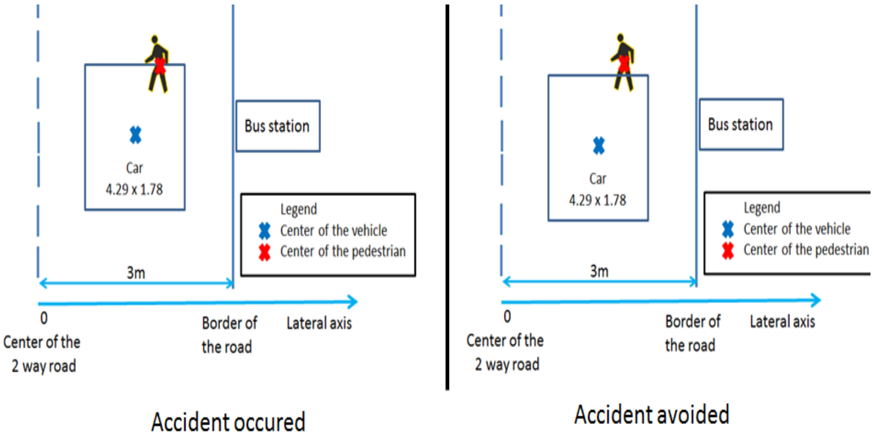


Figure 5: pedestrian center is inside the area of the car, so an accident occurs (left) and pedestrian center is outside the area of the car, so the accident is avoided (right).

Participants' manoeuvers

We draw participants' manoeuvers to show how they react to the appearance of the pedestrian on their trajectories. This visually indicates if a participant hit the pedestrian and if he tries a steering manoeuver or not. The sequence ends when participant hit the pedestrian or when the vehicle stops without hitting the pedestrian.

Gaze location

Here is the method used to determine Region Of Interest (ROI) for eye tracker data. First we determine regions of interest on the Field Of View (FOV) of each participant. Then we gather gaze location to see in which region are located gaze positions from the moment the pedestrian becomes visible to the collision or to the halt of the vehicle.

Definition of Regions Of Interest

As we have no record of the driving scenario progress for the pilot study, we will use data from eye tracker to define regions of interest.

First we gather in a figure all gaze locations collected from each participant on the Pedestrian Crossing Nearside scenario as shown in the Figure 6 below.

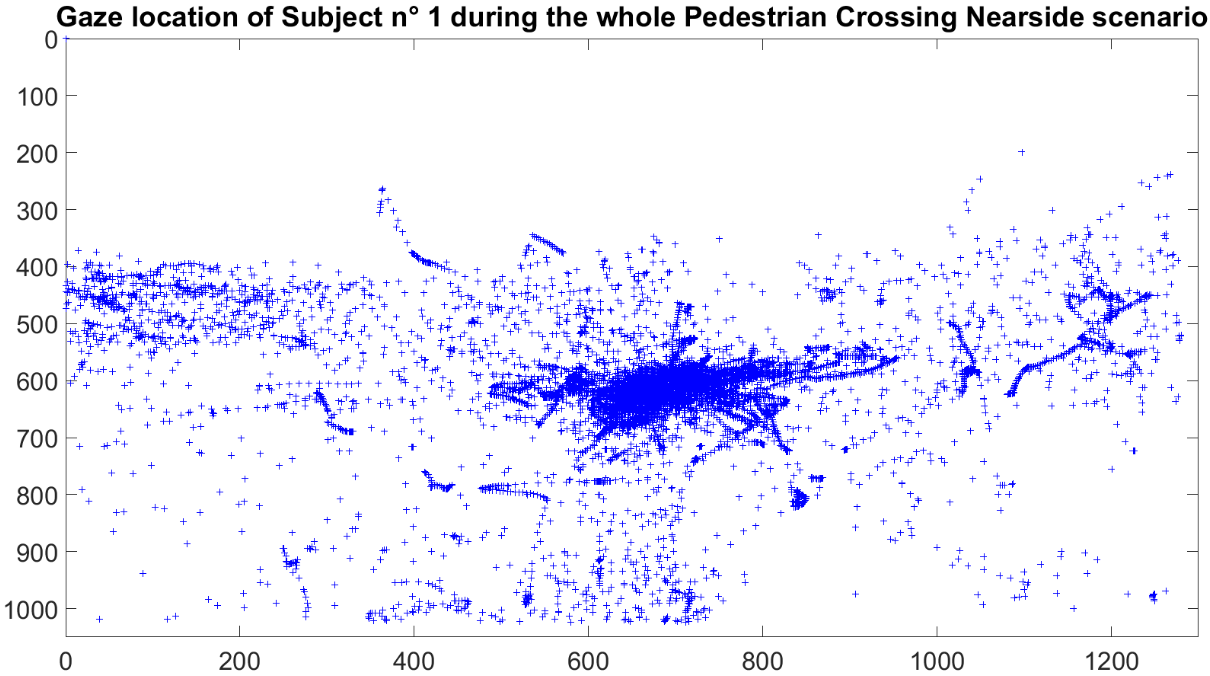


Figure 6: gaze location for Subject 1 for the Pedestrian Crossing Nearside scenario

One important point in the Pedestrian Crossing Nearside scenario is that the scenario is straight. Indeed, participants are instructed to follow IFSTTAR direction. Thus the road to go to IFSTTAR is straight in this scenario. During their driving, as participants do not have to change direction, drivers mostly look the road ahead far away. In this way, we make the assumption that from eye tracker data, there should be a concentrate point cloud that must match to the road far away. From here, we are able to determine the region from that point cloud. The delimitation of the limit of road region is done visually, so the results obtained rely on the precision of the defined region. On the Figure 7, we show the region obtained from the point cloud of participant number 1.

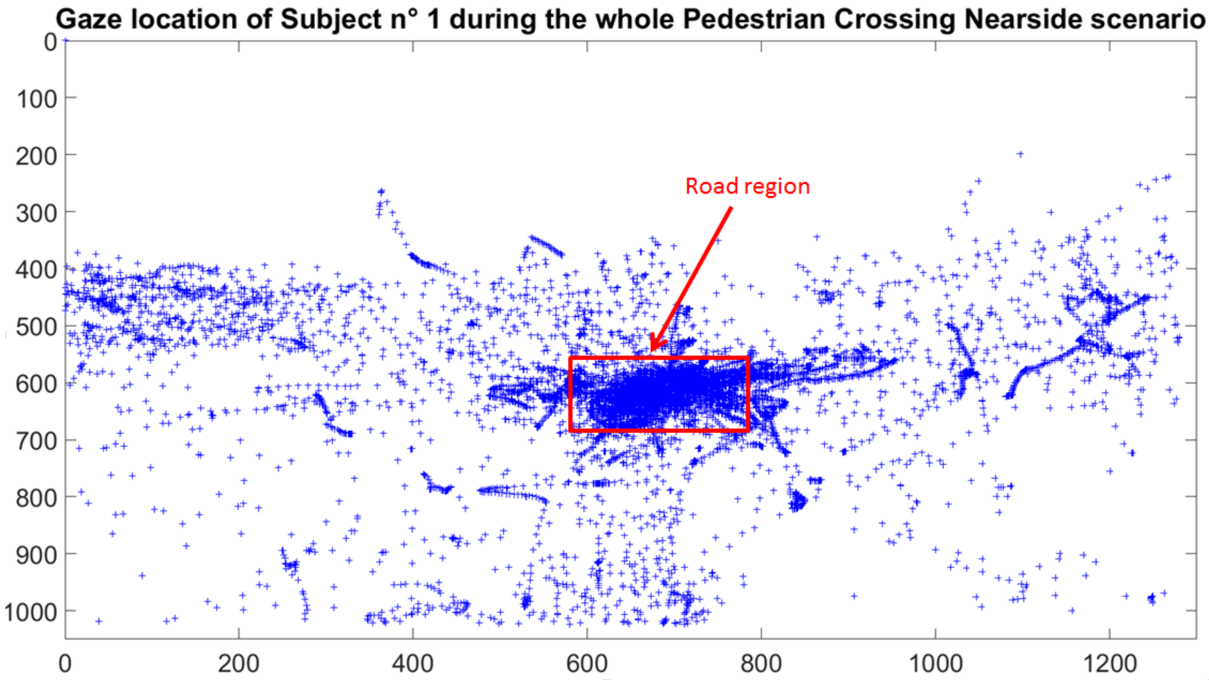


Figure 7: definition of road region

After the definition of the road region, we are able to divide the rest of the test participant field of view as shown in the Figure 8 below. There are 10 zones, 1 to 10. Region 10 corresponds to signal loss for example when gaze is off eye tracker or when participant blinks. It is represented by all gaze location points which coordinates are (0,0).

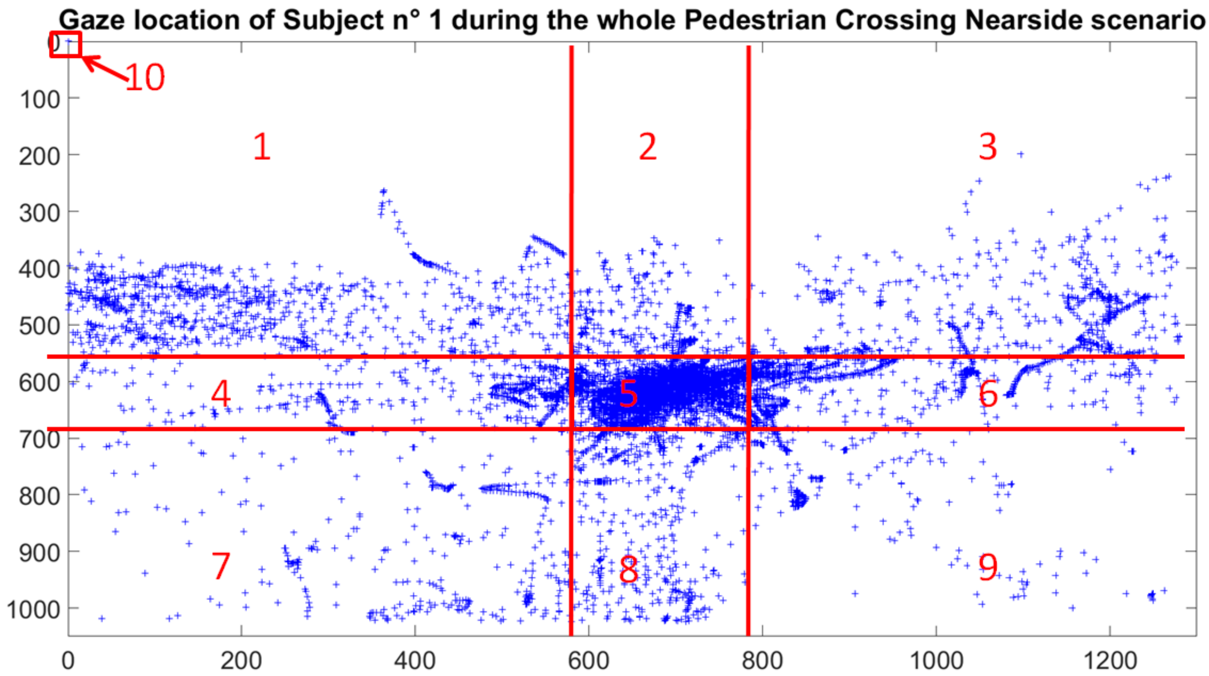


Figure 8: Regions of interest for test participant 1

We repeat this method for each participant as they all have different driving position in the driving simulator vehicle and as participants' position on the driving scenario are different.

Finally we obtain a graph that indicates in which area of interest is located participants' gaze.

Gas and brake pedal stroke with vehicle instant speed

Participants' action on gas and brake pedal has been recorded. We extract both pedals stroke from driving simulator files. On driving simulator files, ranges values for gas and brake pedal stroke are between 0 to 255, 0 means no stroke on pedal and 255 means maximum stroke on pedal. The results are shown from the moment the pedestrian becomes visible to the moment of either the vehicle impacts the Pedestrian, either when the vehicle stops in front of the Pedestrian avoiding him. Additionally, the instant speed of the car is added on the graph. Speed of vehicle is given in driving simulator files by the variable.

Cyclist Longitudinal

Here is a list of variable analyzed for the Cyclist Longitudinal scenario:

- Drivers' manoeuver
- Gas and brake pedal stroke

Drivers' manoeuver

We describe trajectories of participants from when participants' vehicle and the Cyclist are on the same road until the vehicle speed becomes lower to the Cyclist one which is 5.007m/s. Participant's vehicle is considered to be on the same road as the Cyclist when the variable for the vehicle has the same value as for the Cyclist. The choice of this moment to end the sequence of analysis is based on the fact that nobody hit the Cyclist when approaching him.

Gas and brake pedal stroke

Exact method as previously described. The results are shown from the moment participants' vehicle and the Cyclist are on the same road to the moment when participants' speed is lower than the Cyclist one (5.007m/s).

Sample description

The following figures (Figure 9 to 16) describe the sample of the 20 volunteers regarding to all the parameters acquired on their profiles.

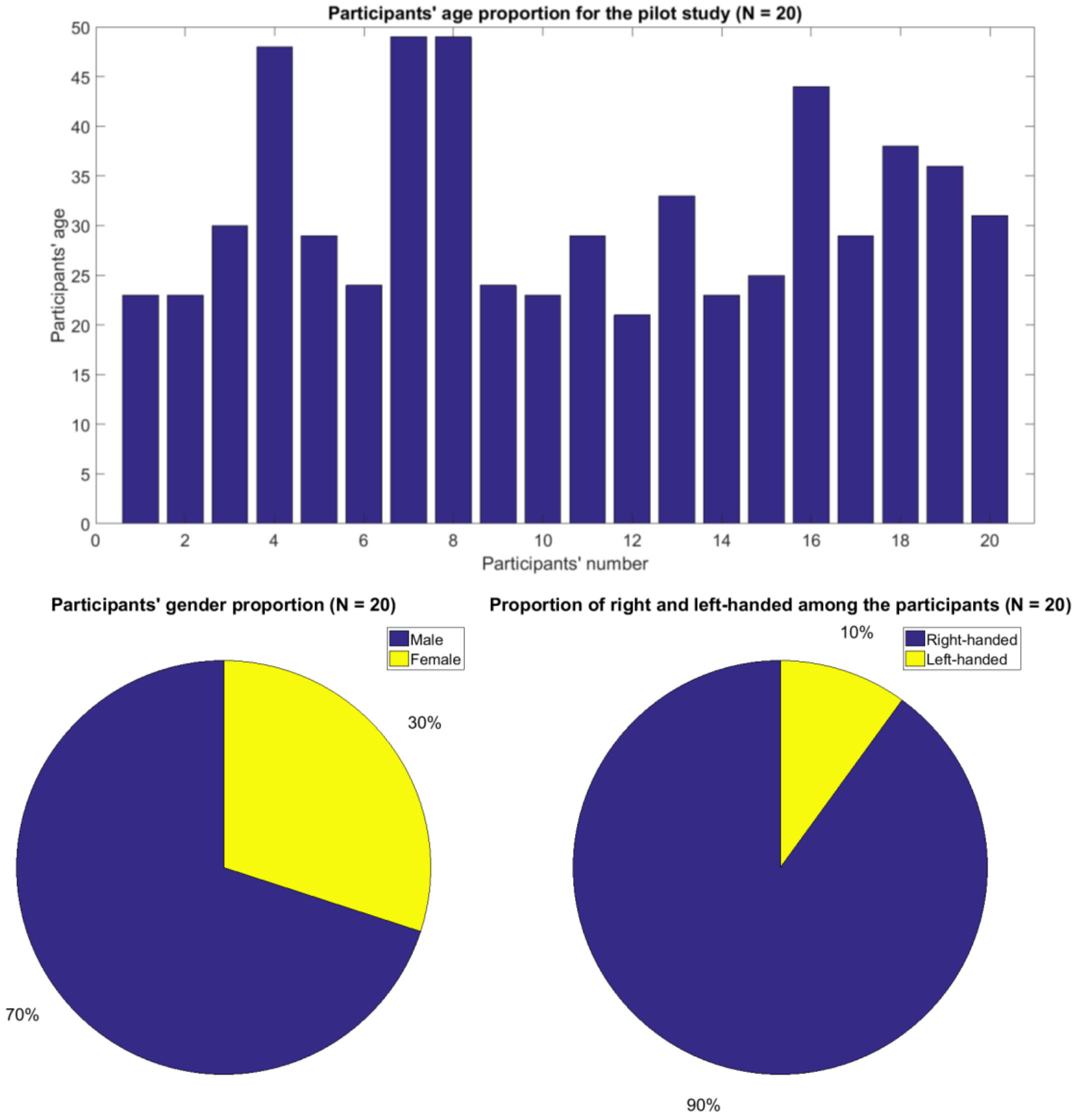


Figure 9: Participants' age proportion. Mean: 31.55 (top). Gender proportion (bottom-left), proportion of right and left-handed people (bottom- right)

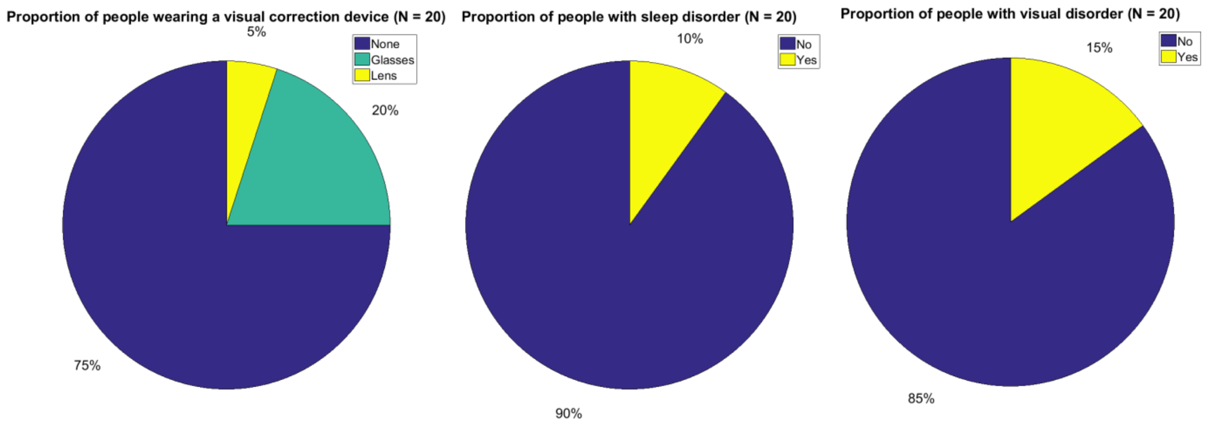


Figure 10: Proportion of people wearing visual correction device for driving (left), people with sleep disorder (center) and people with visual disorder (right)

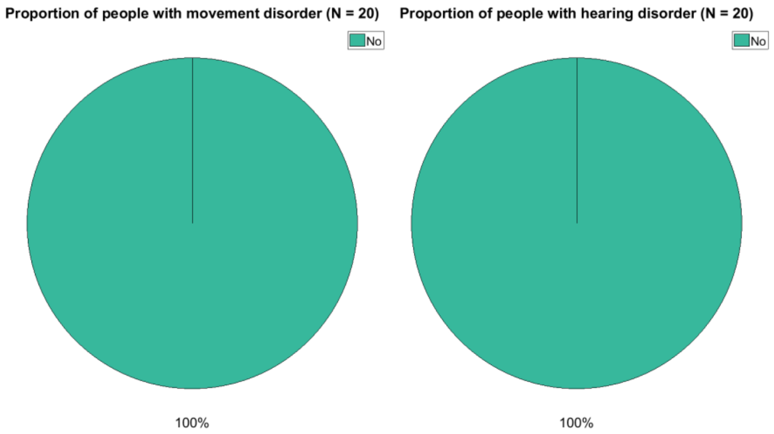


Figure 11: Proportion of people with movement disorder (left) and proportion of people with hearing disorder (right)

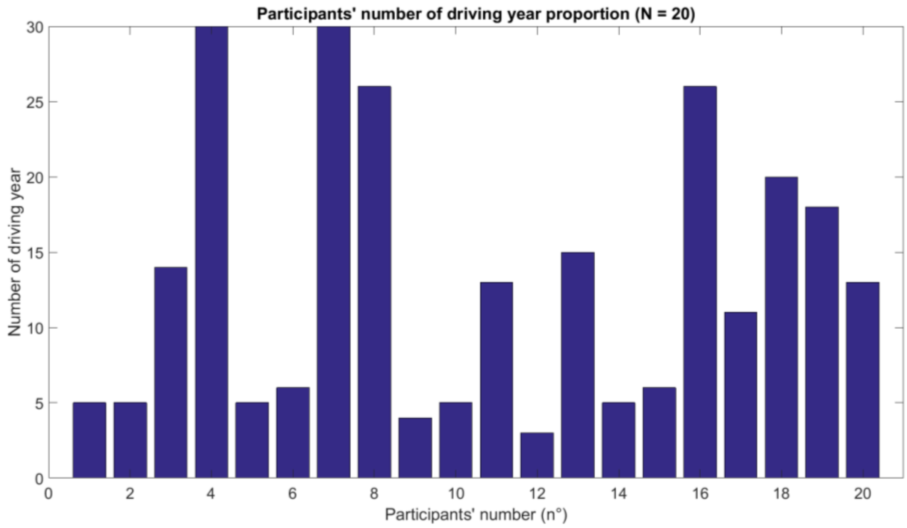


Figure 12: Participants' number of driving year

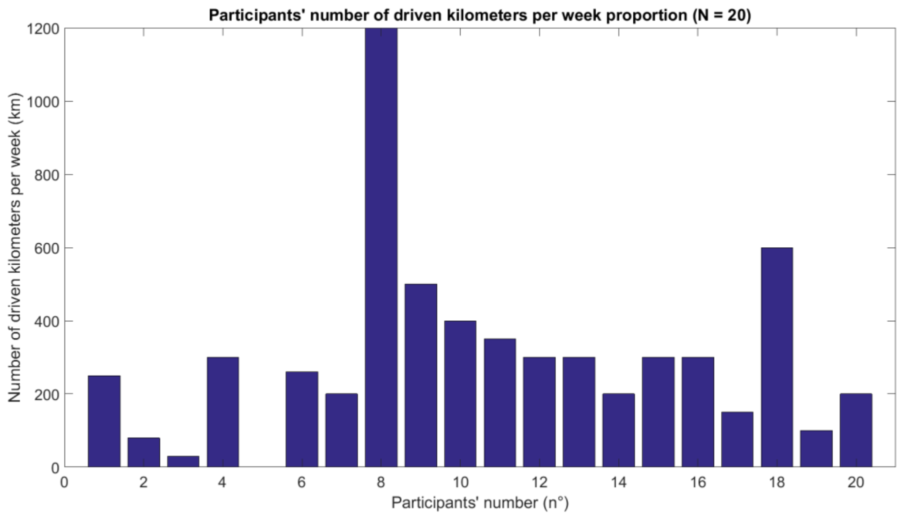


Figure 13: Participants' number of driven kilometers per week (driver n°5 didn't answer)

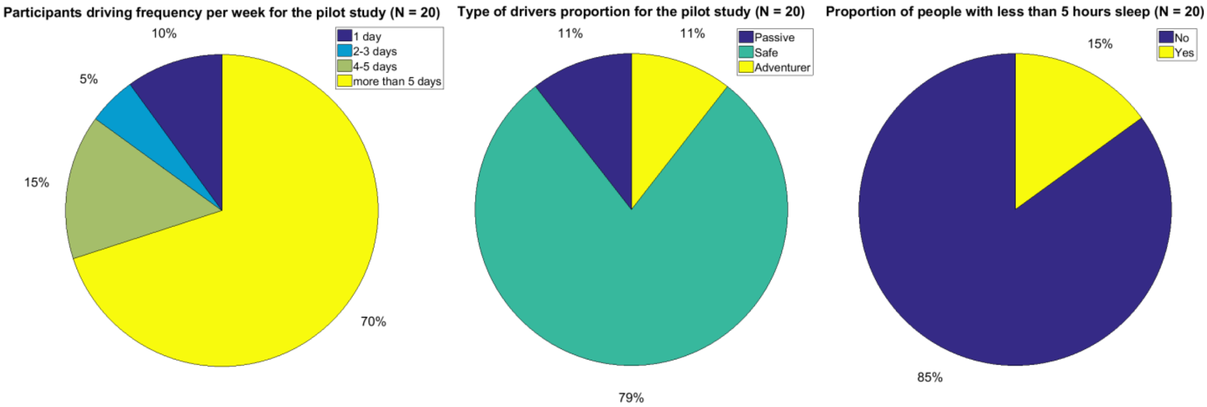


Figure 14: Participants' driving frequency (left), type of drivers (center) and have drivers slept less than 5 hours the night before the experiment (right)

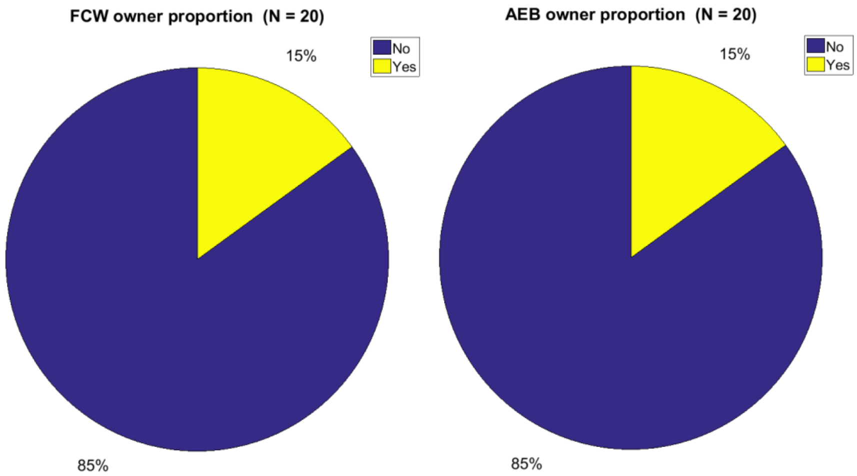


Figure 15: Proportion of drivers having a FCW on the left and proportion of drivers having an AEB

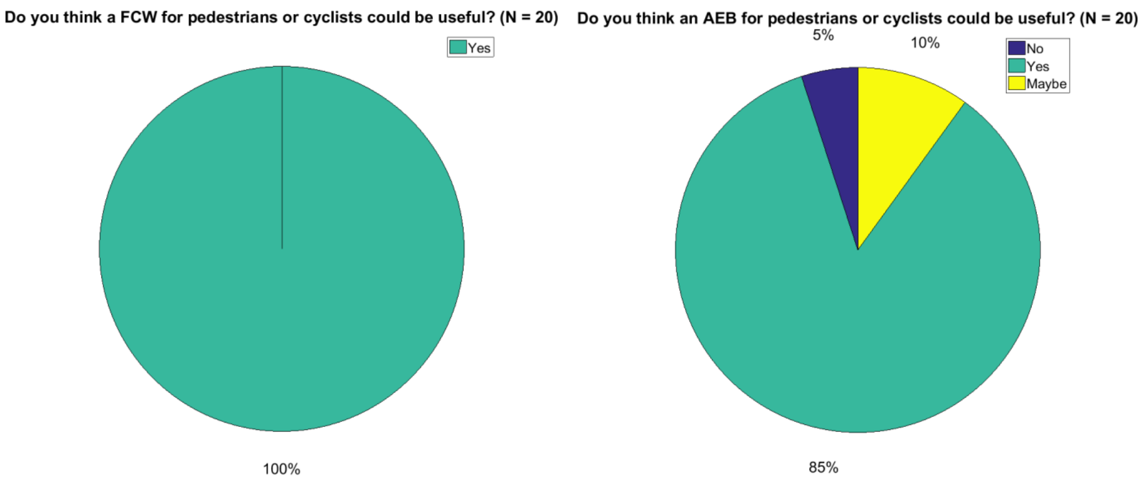


Figure 16: Proportion of people that think that a FCW could be useful (left) and proportion of people that think that an AEB could be useful (right)

Experiment results for Pedestrian Crossing Nearside scenario

Time to release the gas pedal

Figure 17 shows the results for all participants' time to completely release the gas pedal.

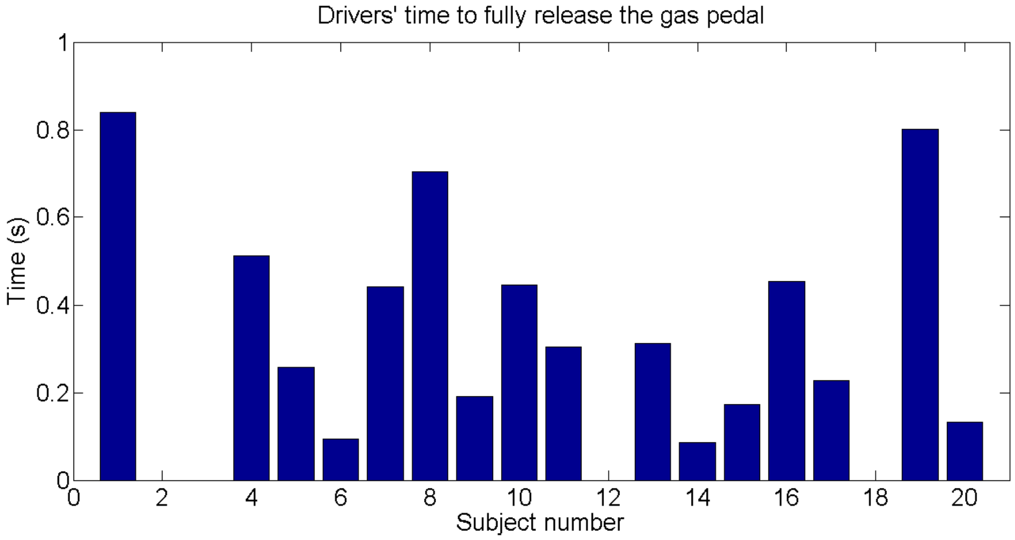


Figure 17: Drivers' time to completely release the gas pedal from when the pedestrian becomes visible

A Student test has been performed to analyze if there is a difference between people who experiment the Pedestrian Crossing Nearside scenario at their 1st tested scenario and people who experiment the scenario during their 2nd tested scenario. There were 10 people who experiment the scenario at their 1st tested scenario and 10 at their 2nd tested scenario.

People who completely release the gas pedal before the pedestrian was visible were not considered. There were only 7 people in the group of those who experiment the scenario during their 1st tested scenario (1st group) and 9 in the group of those who experiment the scenario during their 2nd tested scenario (2nd group).

We test the hypothesis H_0: there is no difference between both groups.

The mean time value for the 1st group is **0.3549s** whereas the mean value is **0.3876s**.

The standard deviation for the 1st group is **0.2514s** and **0.2491s** for the 2nd group.

We use the following formula:

$$z = \frac{m1 - m2}{\sigma\sqrt{\frac{1}{n1} + \frac{1}{n2}}}$$

With

$$s = \sqrt{\frac{n1s1^2 + n2s2^2}{n1 + n2 - 2}}$$

m1, m2: mean value for 1st and 2nd group

n1, n2: size of each group

s1, s2: standard deviation

z = -0.2425
We do not reject the H_0 hypothesis.

Time to begin to push the brake pedal

Figure 18 shows the results of all participants time to begin to push the brake pedal. Red color corresponds to participants who hit the pedestrian whereas blue corresponds to no collision.

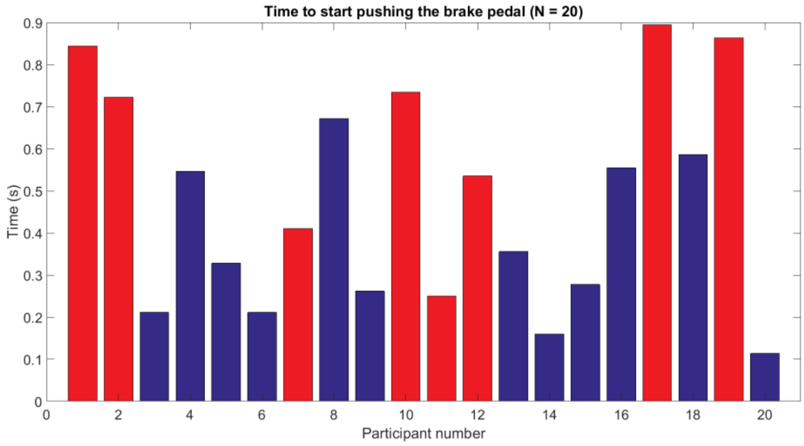


Figure 18: Drivers' time to begin to push the brake pedal

The same Student test as mentioned in the gas pedal release time has been used to determine if there is a difference between the 2 groups (H0 hypothesis).
The mean value for 1st group is **0.6121** and **0.7215** for the 2nd group.
The standard deviation is **0.2253** for the 1st group and **0.2794** for the 2nd group.

z = -0.4619
We do not reject H0 hypothesis.

Number of accidents and collision speed

Figure 19 shows the number of collision for all participants. Figure 20 shows the number of collisions when Pedestrian Crossing Nearside (P-CN) is the 1st experimented scenario whereas Figure 21 shows the number of collision when P-CN is the 2nd experimented scenario.

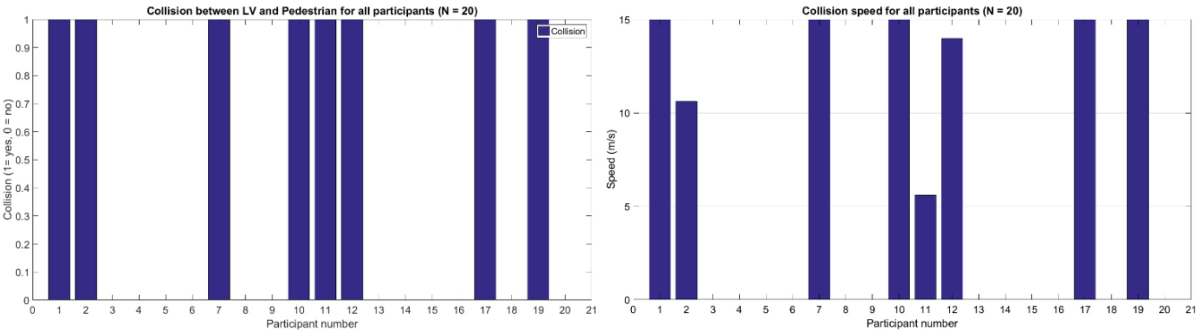


Figure 19: Number of collisions (8 out of 20) on the left and collision speed on the right. Mean value and standard deviation: 13.1478 (3.4107). Min value: 5.5900 and max value: 15.

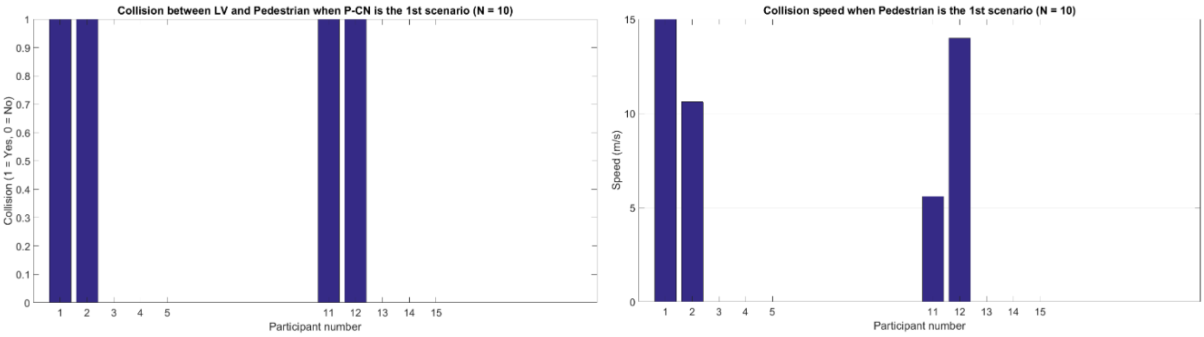


Figure 20: Results when Pedestrian CN is the 1st scenario. Number of collisions (4 out of 10) on the left and collision speed on the right. Mean value and standard deviation: 11.2955 (4.2420). Min value: 5.5900 and max value: 15.

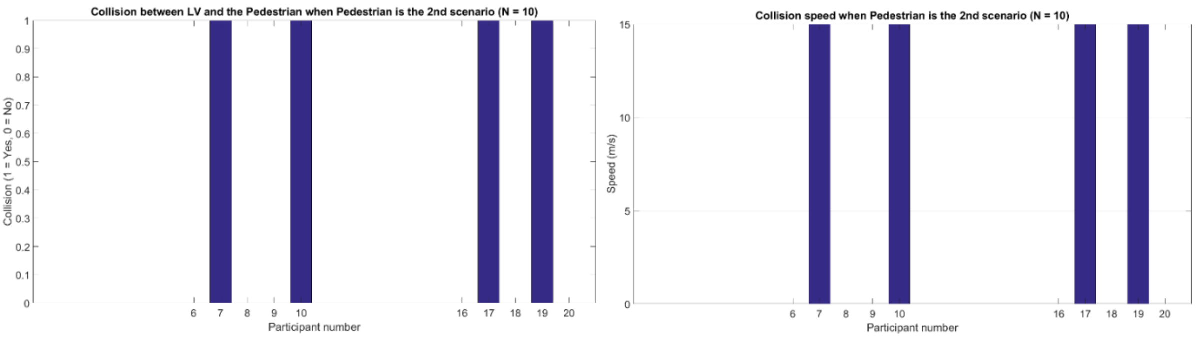


Figure 21: Results when Pedestrian CN is the 2nd scenario. Number of collisions (4 out of 10) on the left and collision speed of the right. Mean value and standard deviation: 15 (0). Min value: 15 and max value: 15.

Drivers' manoeuvers

In the two figures below, we show drivers' manoeuvers. In the first figure, we have participants that have tested the P-CN in 1st scenario and in the 2nd figure participants that have tested it in 2nd scenario. Horizontally in red, we have the pedestrian walking. Vertically we have drivers' trajectories. When drivers collide with the Pedestrian, the trajectory is drawn in red otherwise the trajectory is drawn in green.

Figure 22 shows drivers who experienced the Pedestrian Crossing Nearside scenario at their 1st scenario. We can see that Subject n°13 try a steering manoeuver and avoid the impact with the Pedestrian.

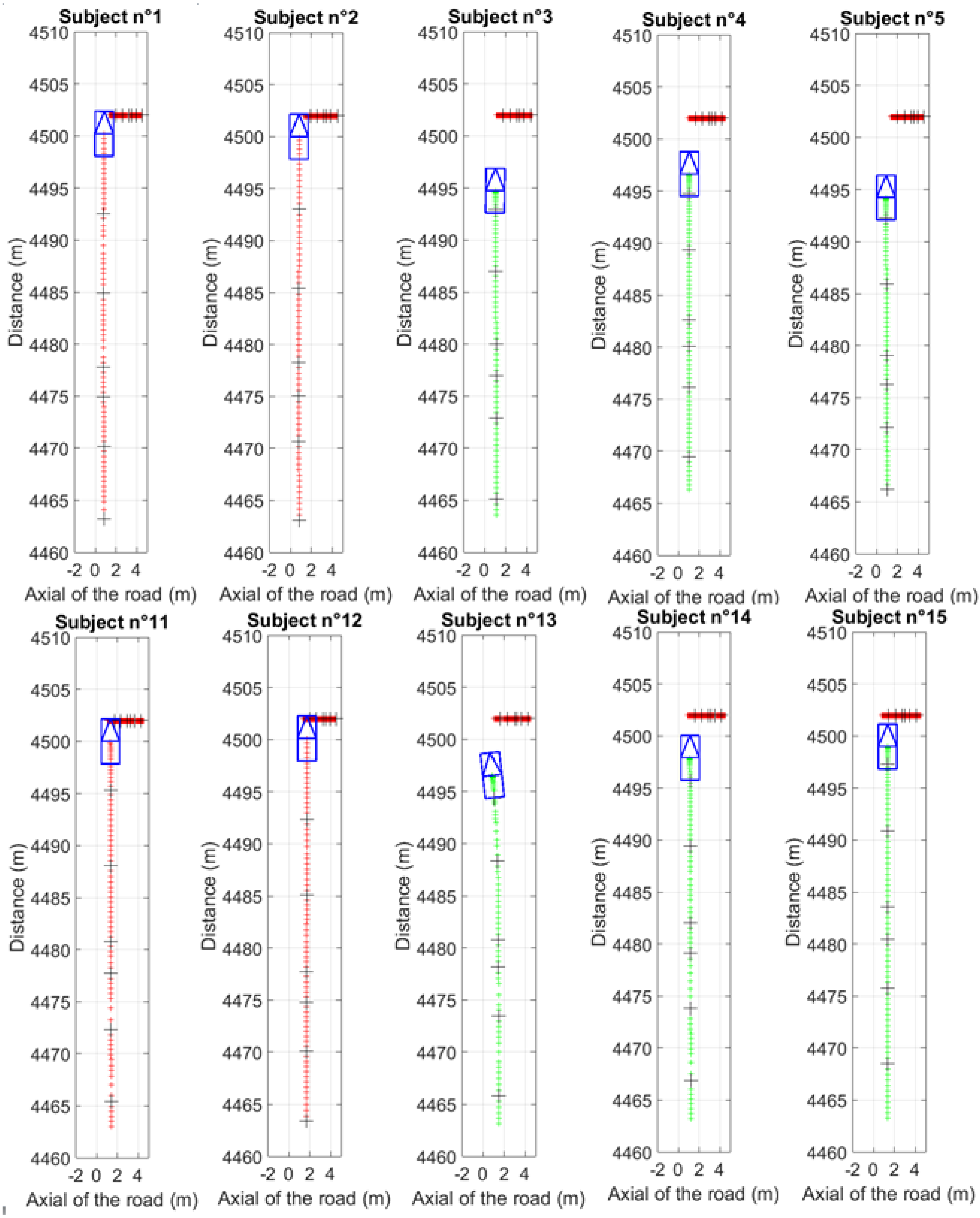


Figure 22: drivers' manoeuvers for the group where Pedestrian Crossing Nearside is the 1st scenario.

Figure 23 shows drivers' manoeuvers for people who experiment the Pedestrian Crossing Nearside at their 2nd scenario. Subject n°17 tries a steering manoeuver but doesn't avoid the impact with the Pedestrian.

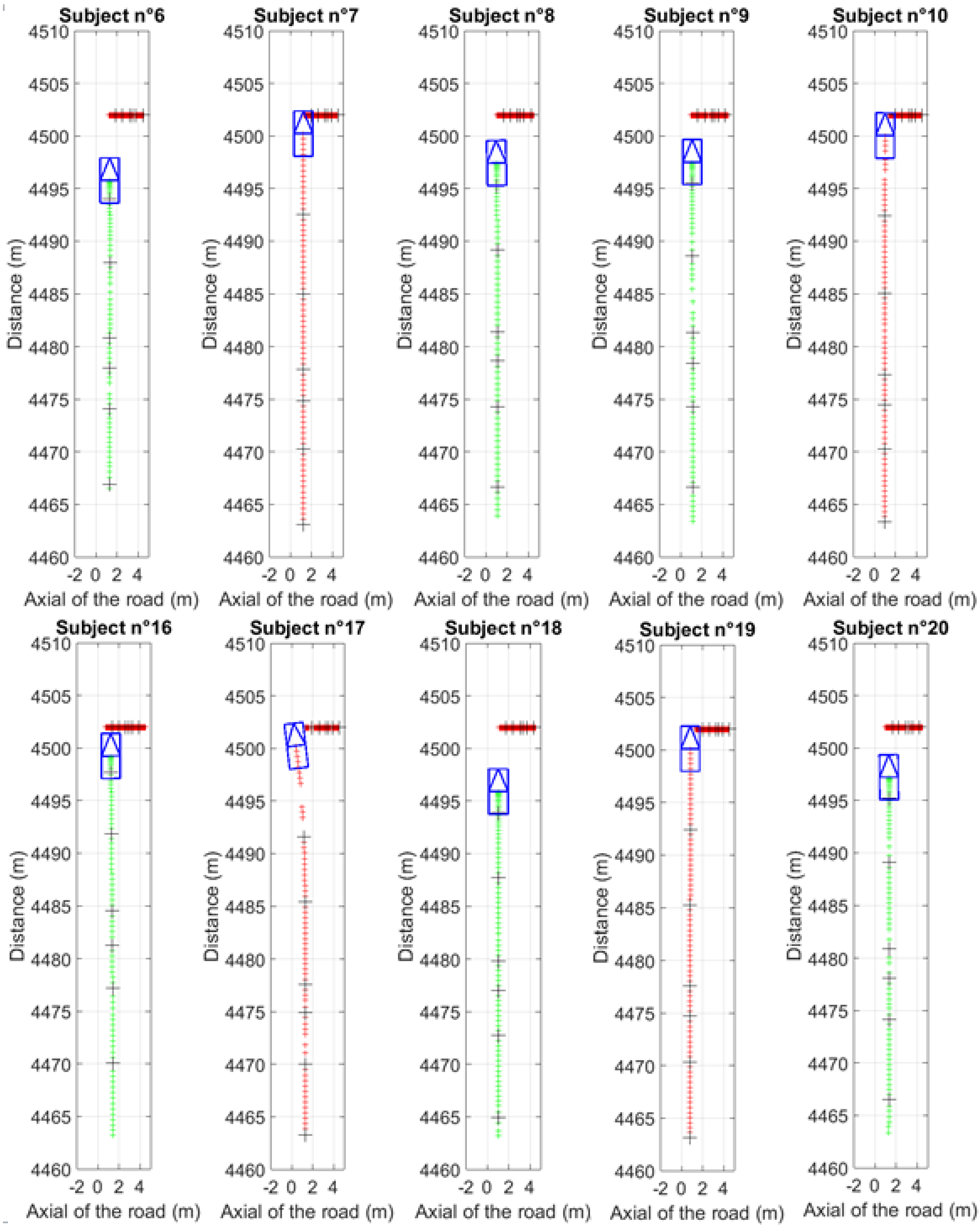
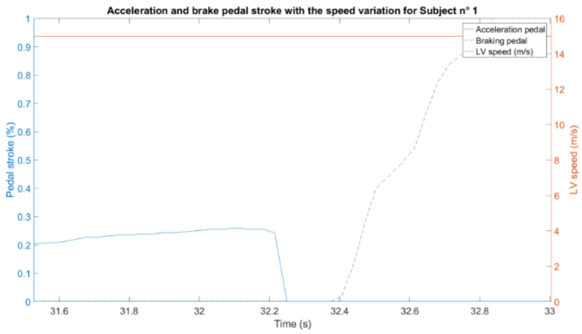
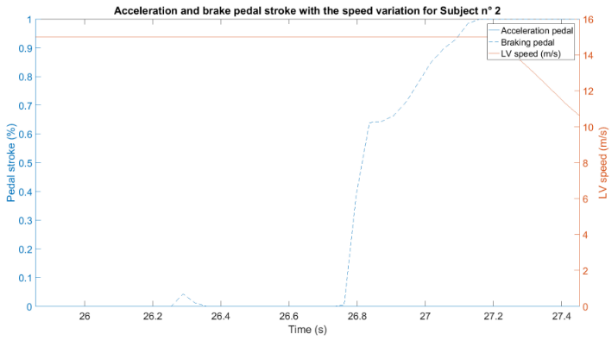


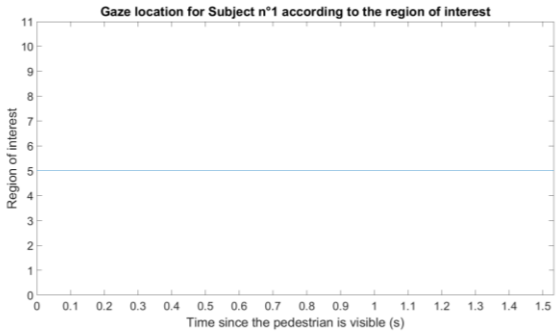
Figure 23: drivers' manoeuvers for the group where Pedestrian Crossing Nearside is the 2nd scenario

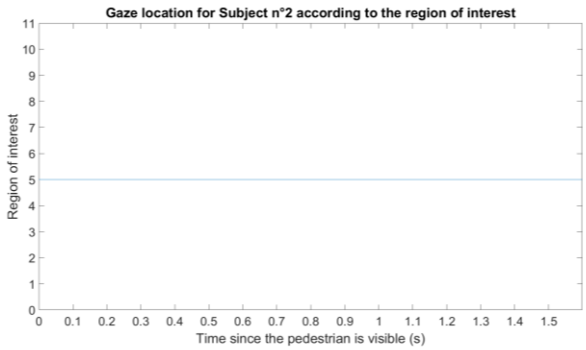
Participants' gaze location and gas and brake pedal stroke

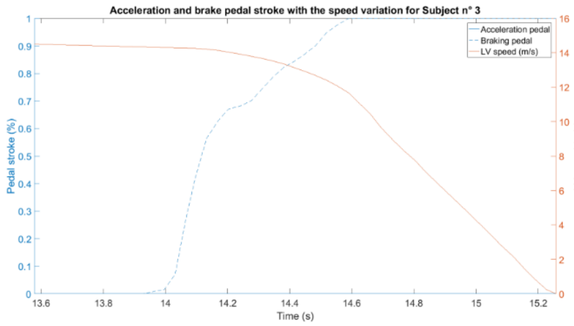
Figures below show the relation between the gaze location, speed and pedal stroke from the moment where the pedestrian is visible to the impact or to the halt of the car. For each participant, the upper graph shows the evolution of speed, gas and brake stroke whereas the graph just below shows the region of interest where the gaze is located. The time scale is the same on the 2 graphs. It starts from the first moment the pedestrian becomes visible to either the moment the car halt or to the moment of the impact.

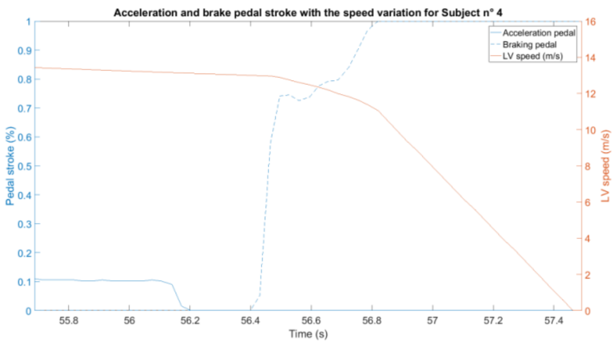


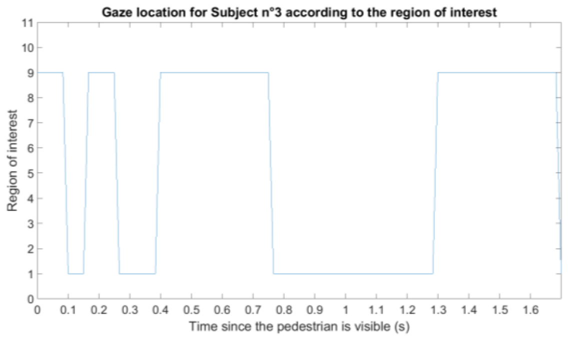


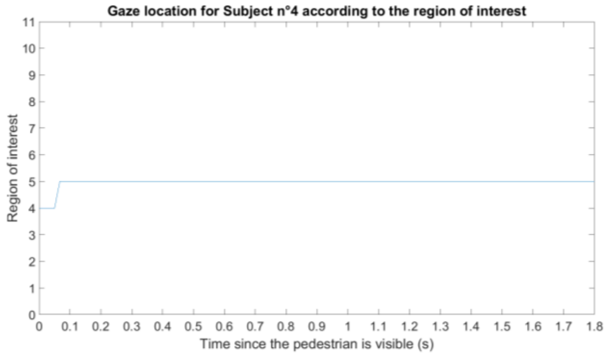


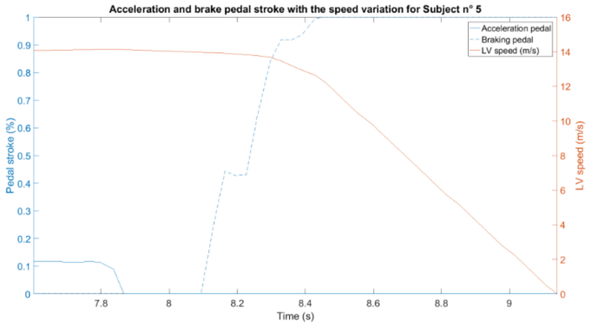


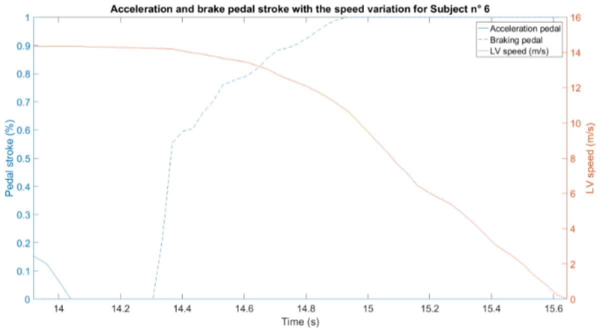


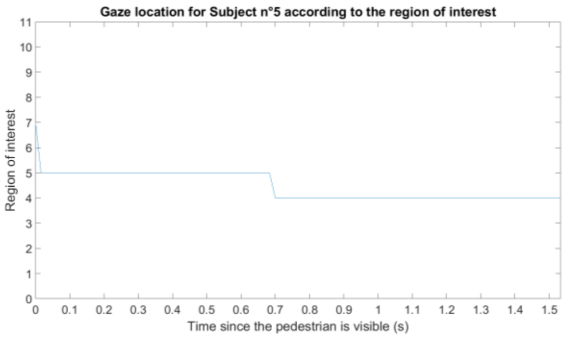


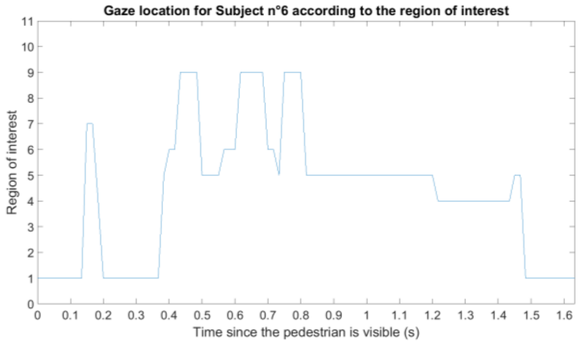


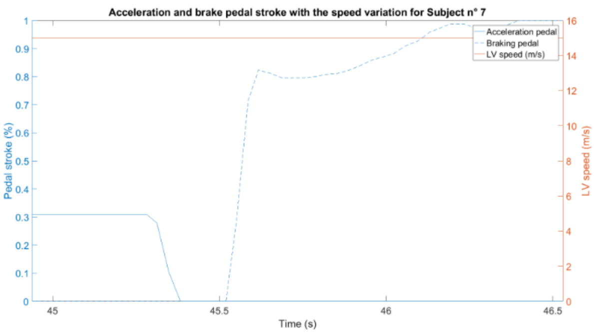


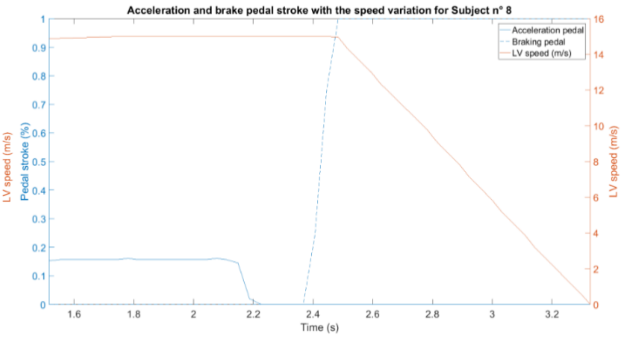

Acceleration and brake pedal stroke with the speed variation for Subject n° 5
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

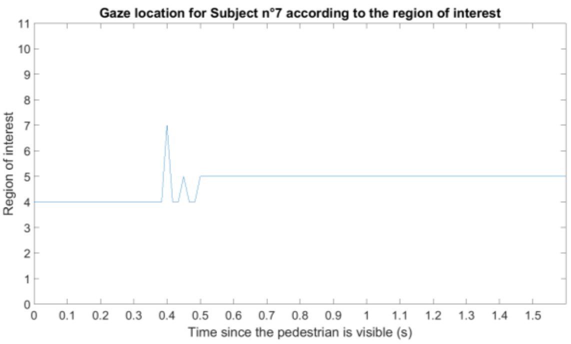

Acceleration and brake pedal stroke with the speed variation for Subject n° 6
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

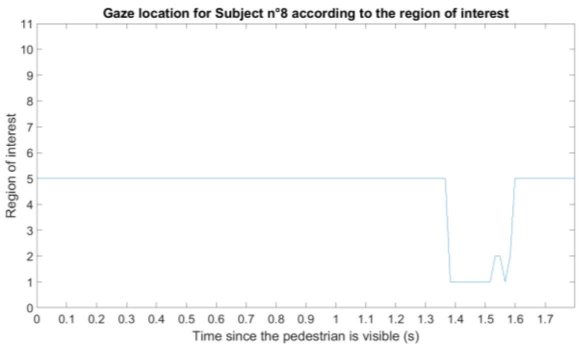

Gaze location for Subject n°5 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

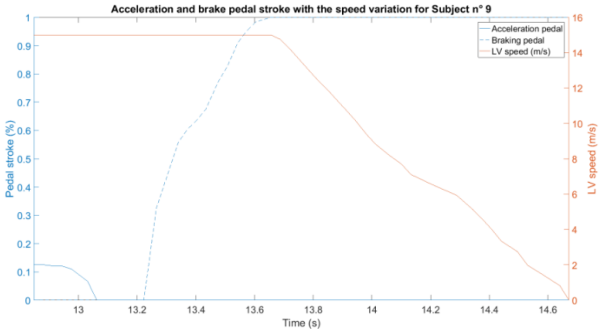

Gaze location for Subject n°6 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

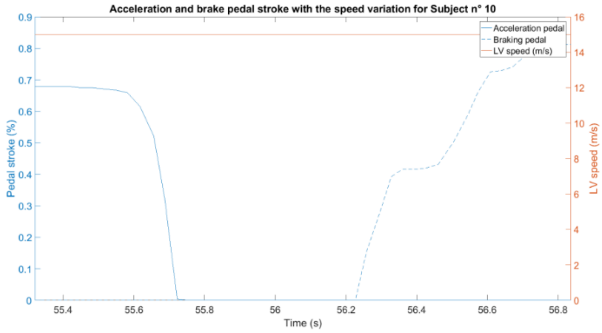

Acceleration and brake pedal stroke with the speed variation for Subject n° 7
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

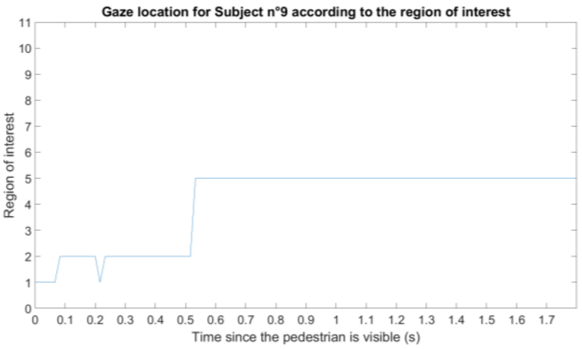

Acceleration and brake pedal stroke with the speed variation for Subject n° 8
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

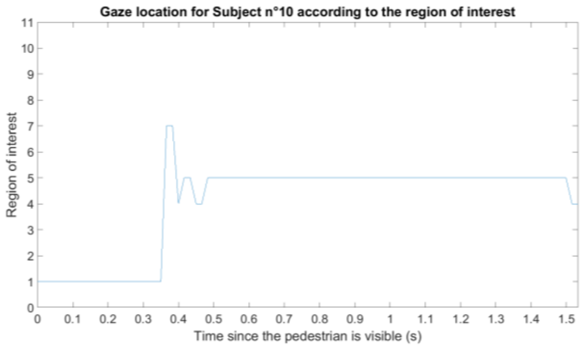

Gaze location for Subject n°7 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

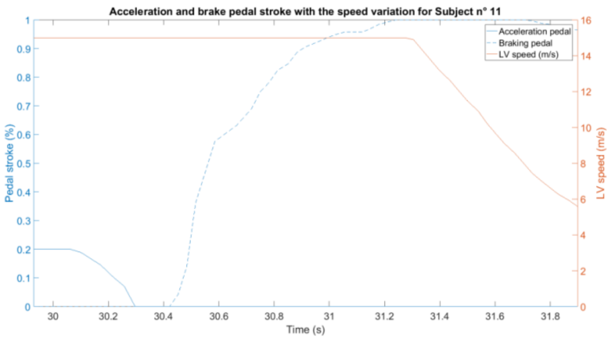

Gaze location for Subject n°8 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

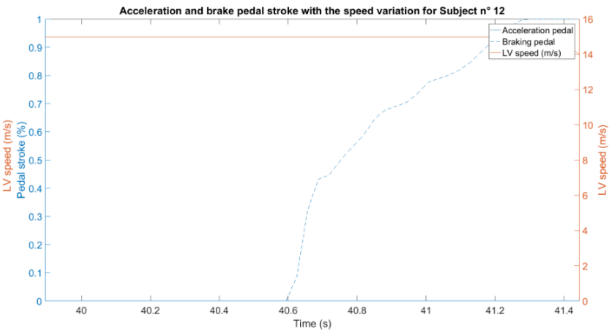

Acceleration and brake pedal stroke with the speed variation for Subject n° 9
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

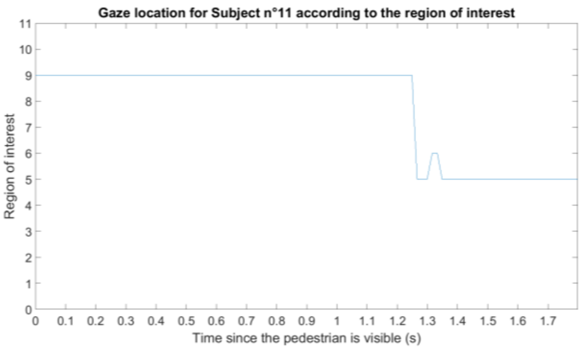

Acceleration and brake pedal stroke with the speed variation for Subject n° 10
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

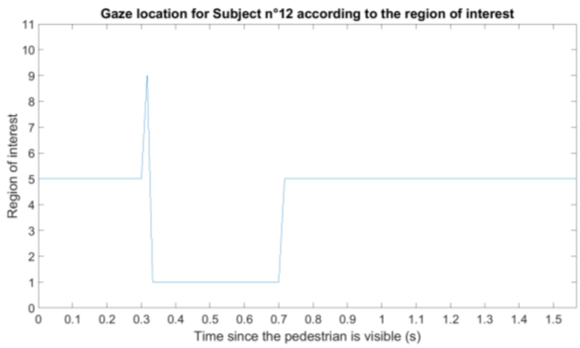

Gaze location for Subject n°9 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

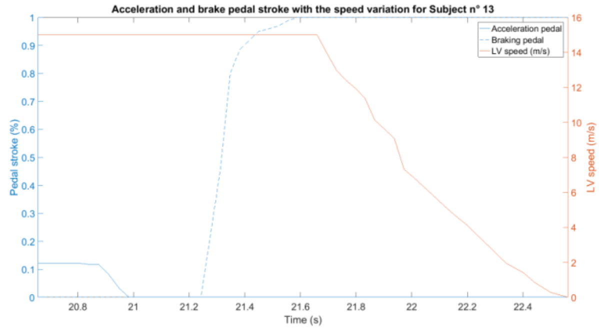

Gaze location for Subject n°10 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

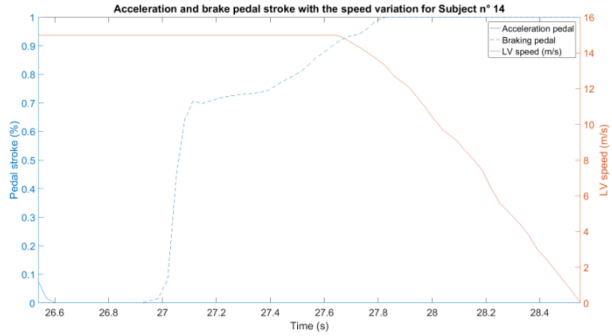

Acceleration and brake pedal stroke with the speed variation for Subject n° 11
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

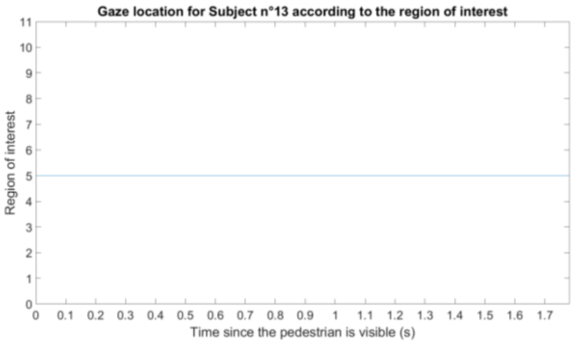

Acceleration and brake pedal stroke with the speed variation for Subject n° 12
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

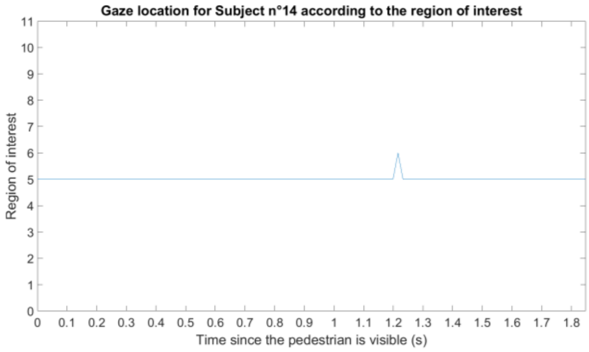

Gaze location for Subject n°11 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

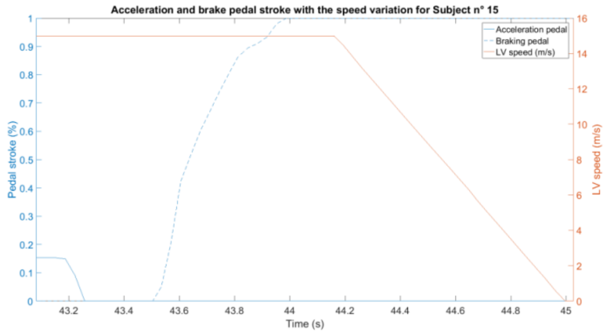

Gaze location for Subject n°12 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

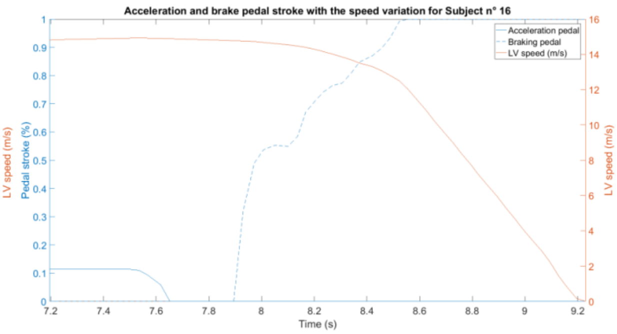

Acceleration and brake pedal stroke with the speed variation for Subject n° 13
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

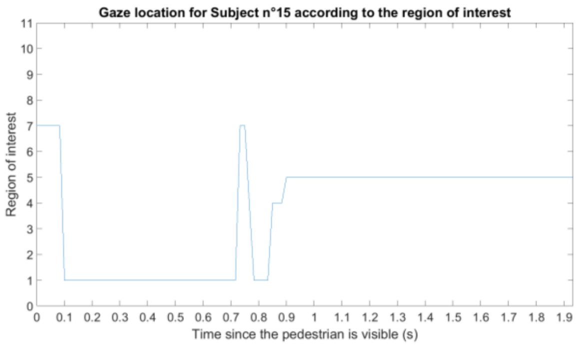

Acceleration and brake pedal stroke with the speed variation for Subject n° 14
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

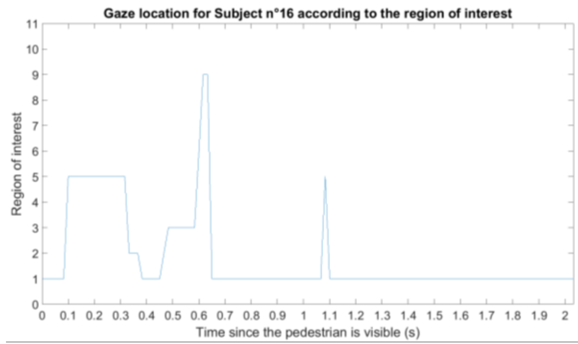

Gaze location for Subject n°13 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)

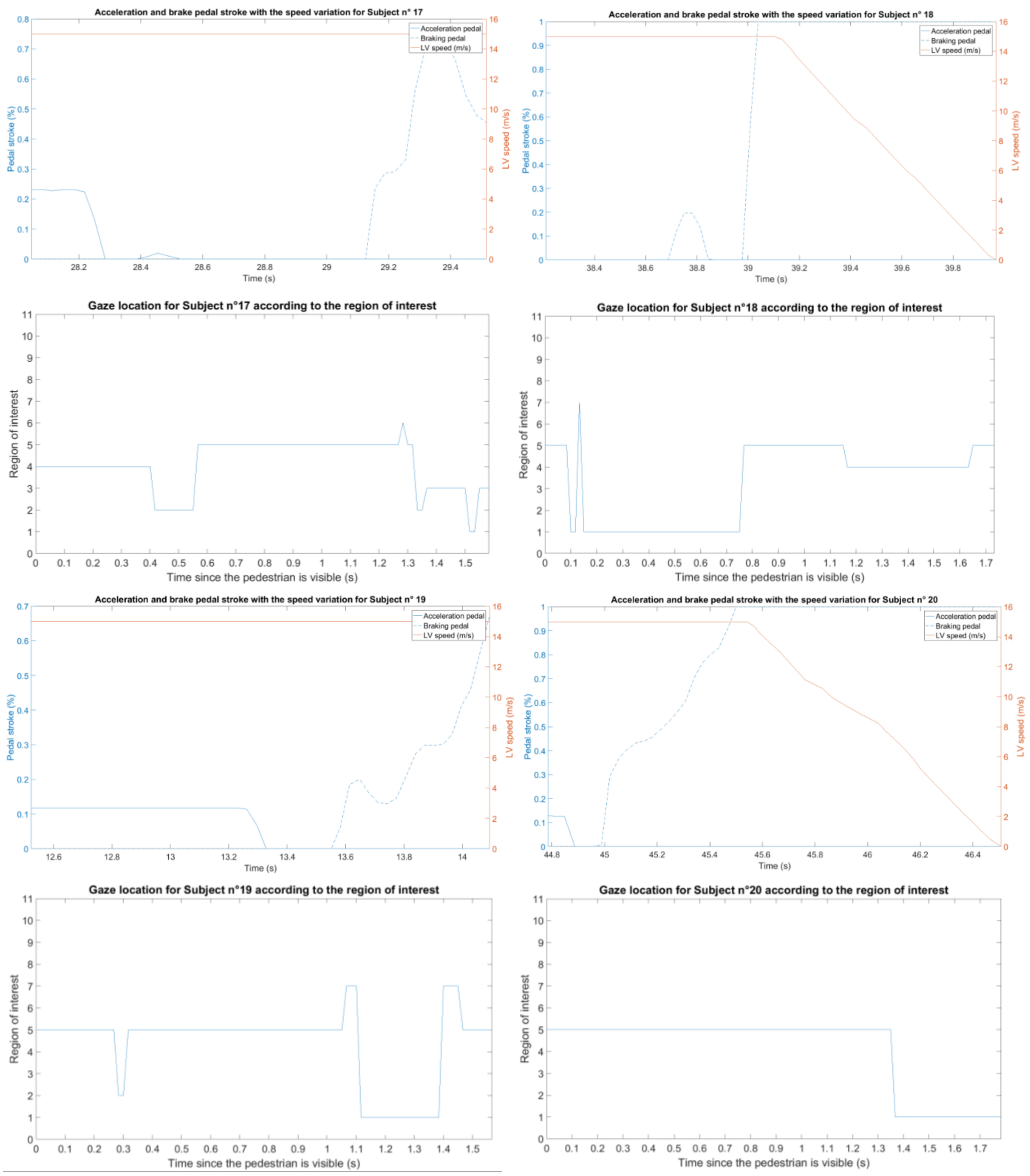

Gaze location for Subject n°14 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)


Acceleration and brake pedal stroke with the speed variation for Subject n° 15
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)


Acceleration and brake pedal stroke with the speed variation for Subject n° 16
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)


Gaze location for Subject n°15 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)


Gaze location for Subject n°16 according to the region of interest
Region of interest
Time since the pedestrian is visible (s)



There is statistically no difference between participants from the first moment they activate the brakes. Most participants seem to have seen the pedestrian crossing as brakes have been triggered. Current analysis is not precise enough to determine exactly what can be perceived as only a region of interest can be determined here. An improvement for gaze analysis can be obtained with the gaze position in the driving simulator environment as described in the conclusion section.

Experiments results for Cyclist Longitudinal

Drivers' manoeuver

In the two figures below (Figure 24 and 25), we show drivers' manoeuvers. In the first figure, we have participants that have tested the Cyclist Longitudinal (C-L) in 1st scenario and in the 2nd figure participants that have tested it in 2nd scenario. In red, we have the Cyclist trajectory and in green we have drivers' trajectories. When drivers collide with the Cyclist, Cyclist and drivers trajectories are drawn in red otherwise the participant's trajectory is drawn in green. Since no collision have been observed, none car trajectories are in red.

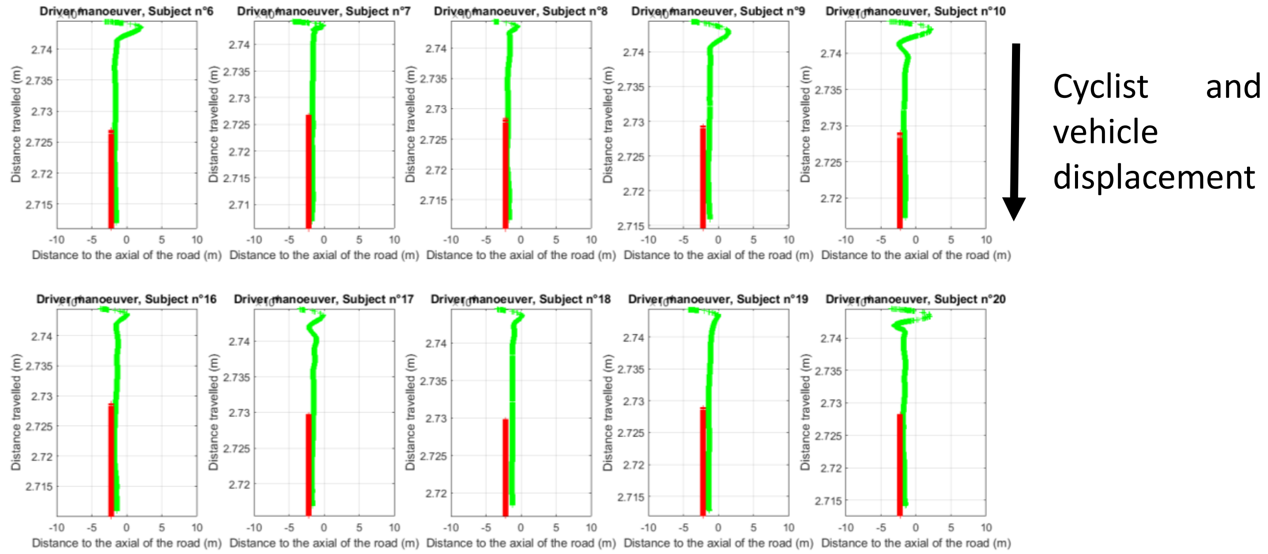


Figure 24: Participants' trajectories from when they are on the same road as the Cyclist to the moment where vehicle speed is lower than the Cyclist one. All participants avoid the accident.

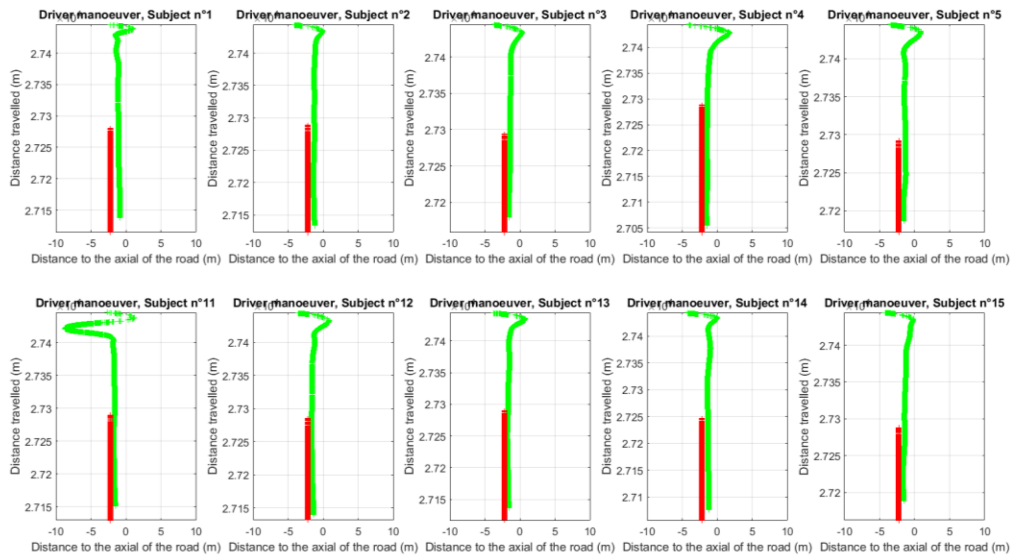
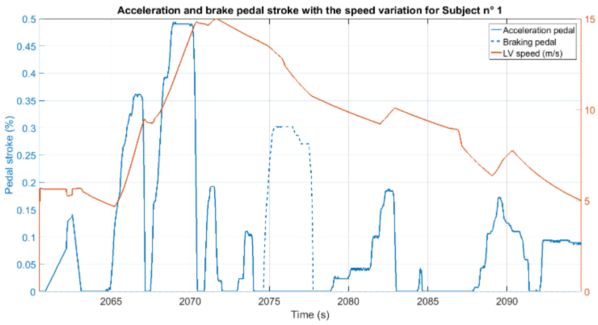
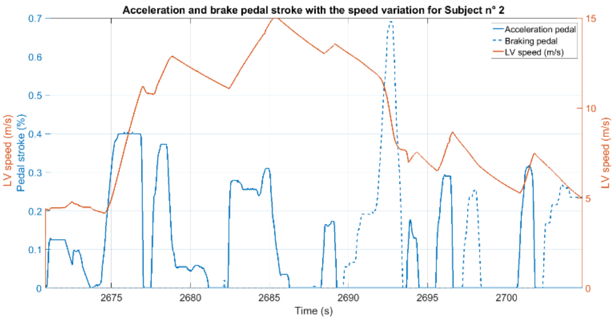


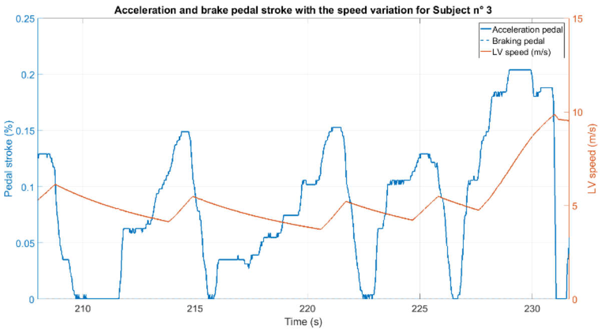
Figure 25: Participants' trajectories from when they are on the same road as the Cyclist to the moment where vehicle speed is lower than the Cyclist one. All participants avoid the accident.

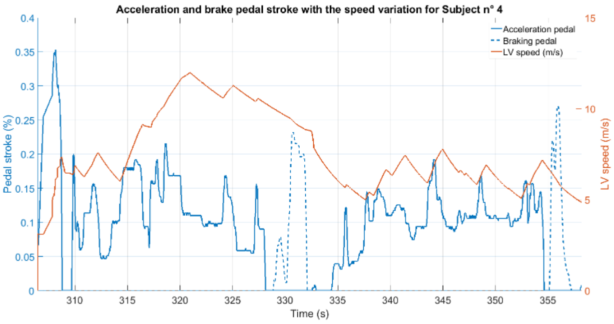
Gas and brake pedal stroke

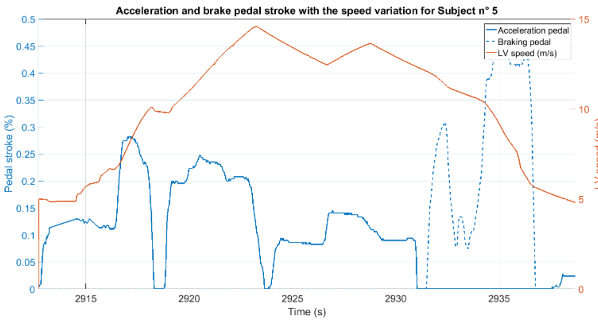
Figures below show participants' action on gas and brake pedal from the moment they are on the same road as the Cyclist to the moment when participants' speed is lower than the Cyclist who rides at a speed of 5.007m/s.

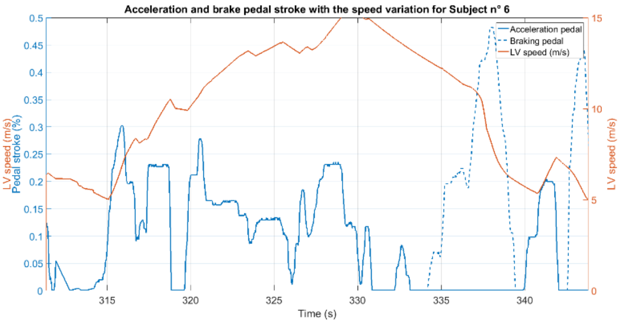

Acceleration and brake pedal stroke with the speed variation for Subject n° 1
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

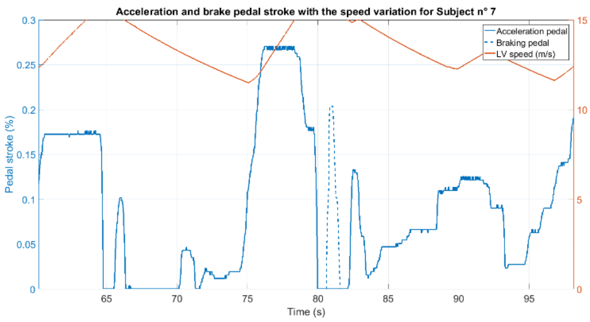

Acceleration and brake pedal stroke with the speed variation for Subject n° 2
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

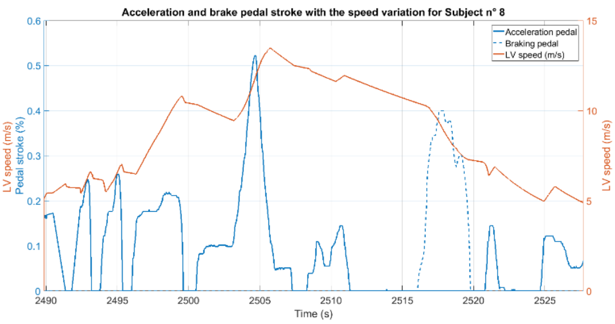

Acceleration and brake pedal stroke with the speed variation for Subject n° 3
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

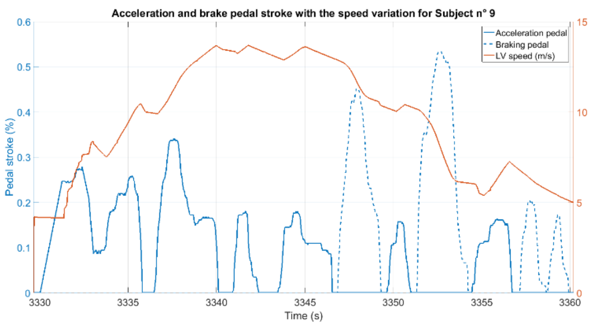

Acceleration and brake pedal stroke with the speed variation for Subject n° 4
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

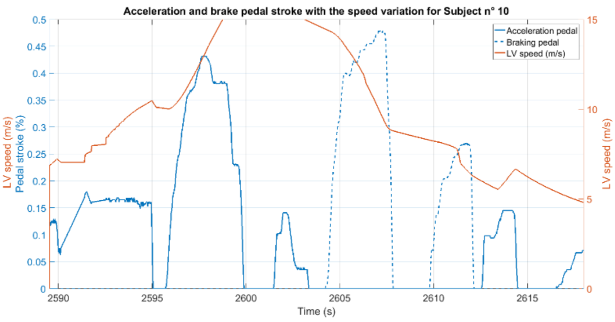

Acceleration and brake pedal stroke with the speed variation for Subject n° 5
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

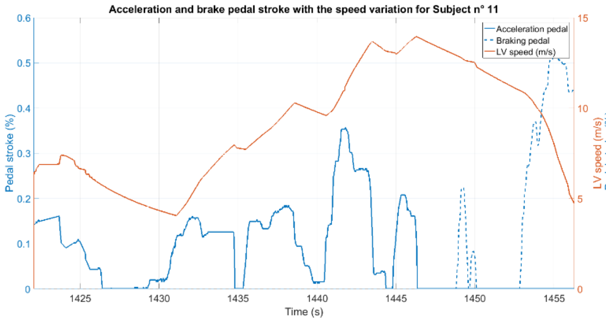

Acceleration and brake pedal stroke with the speed variation for Subject n° 6
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

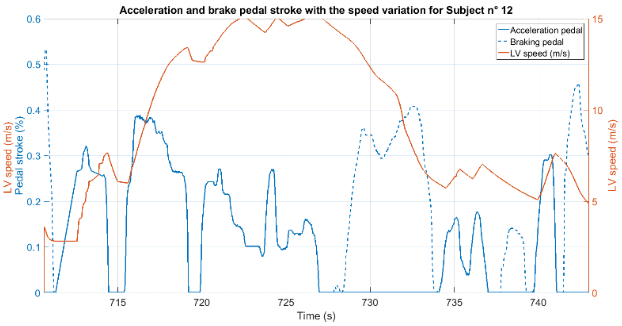

Acceleration and brake pedal stroke with the speed variation for Subject n° 7
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

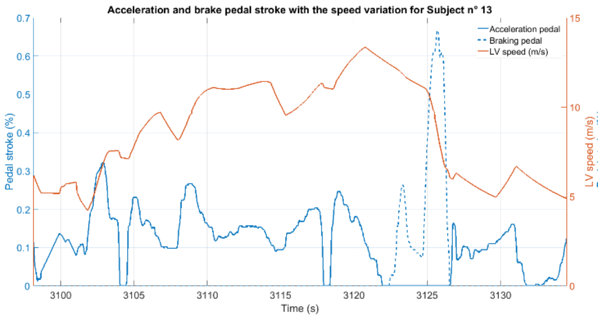

Acceleration and brake pedal stroke with the speed variation for Subject n° 8
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

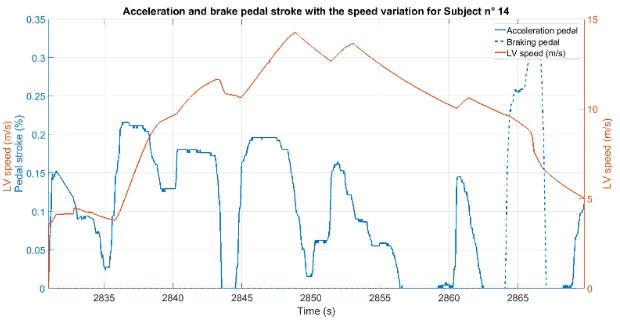

Acceleration and brake pedal stroke with the speed variation for Subject n° 9
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

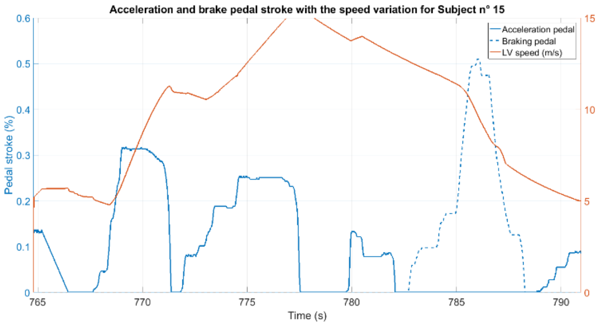

Acceleration and brake pedal stroke with the speed variation for Subject n° 10
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

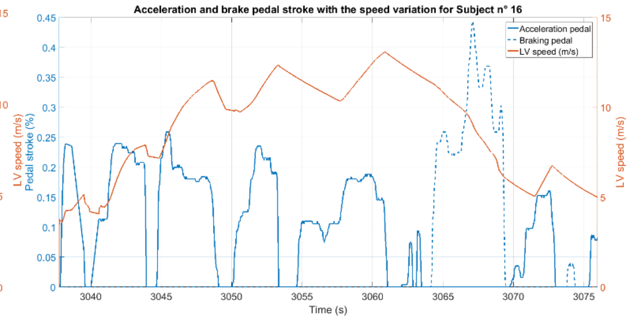

Acceleration and brake pedal stroke with the speed variation for Subject n° 11
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

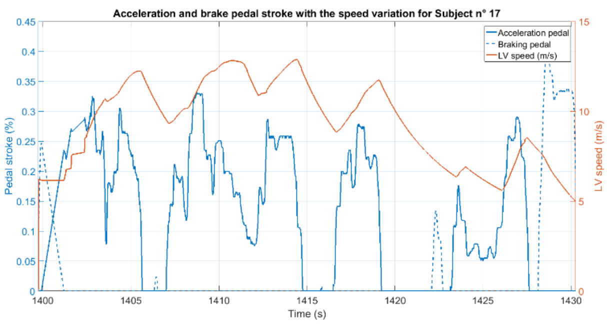

Acceleration and brake pedal stroke with the speed variation for Subject n° 12
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

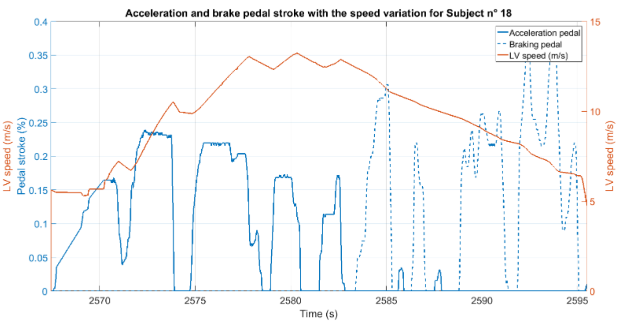

Acceleration and brake pedal stroke with the speed variation for Subject n° 13
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

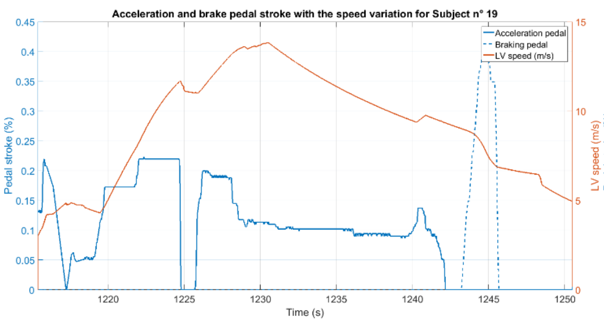

Acceleration and brake pedal stroke with the speed variation for Subject n° 14
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

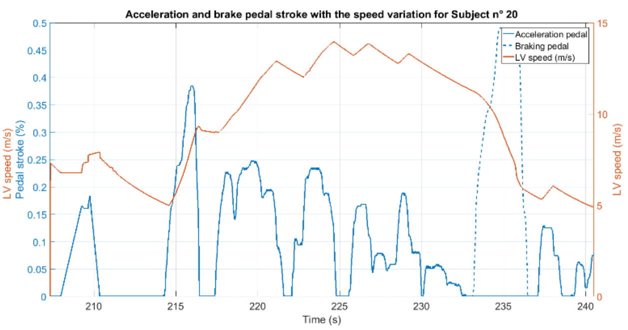

Acceleration and brake pedal stroke with the speed variation for Subject n° 15
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)


Acceleration and brake pedal stroke with the speed variation for Subject n° 16
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)


Acceleration and brake pedal stroke with the speed variation for Subject n° 17
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

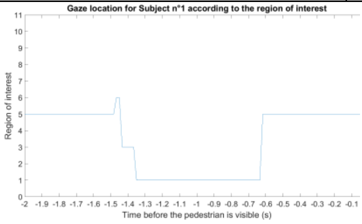
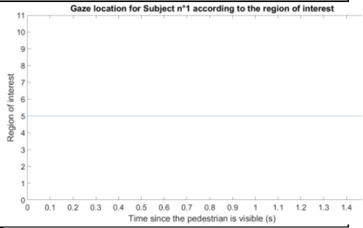
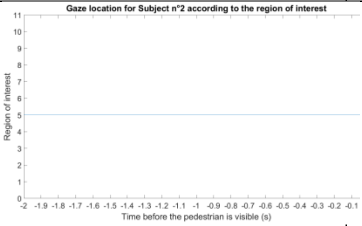
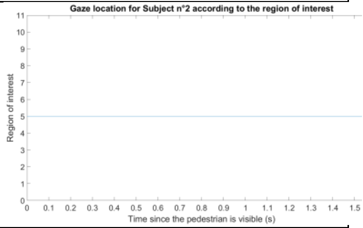
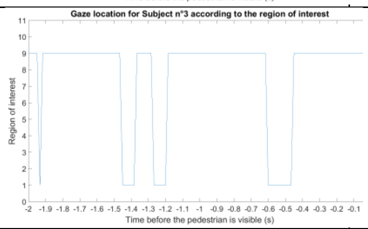
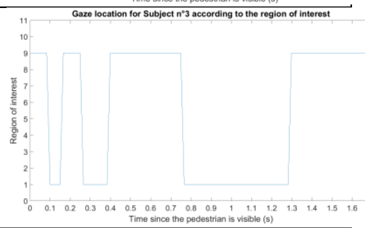
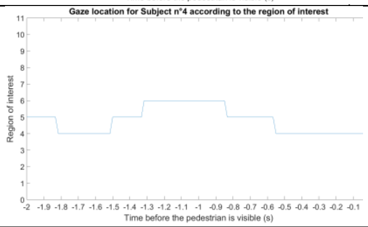
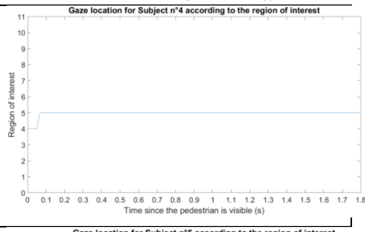
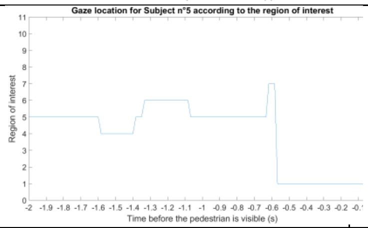
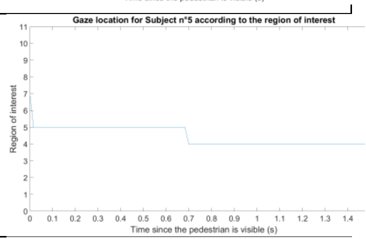
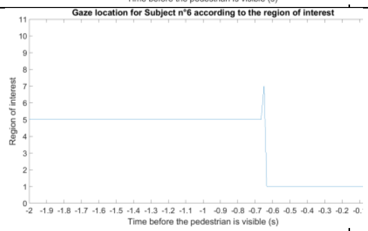
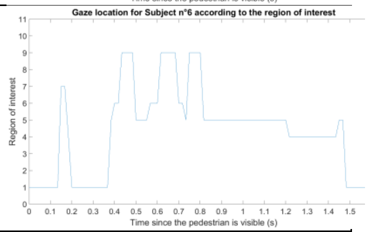

Acceleration and brake pedal stroke with the speed variation for Subject n° 18
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

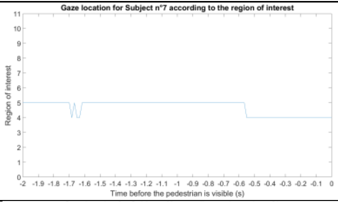
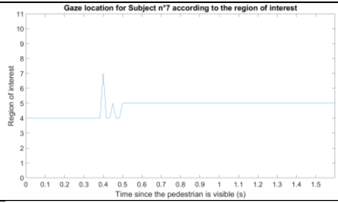
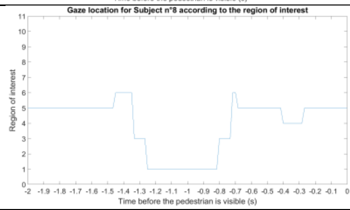
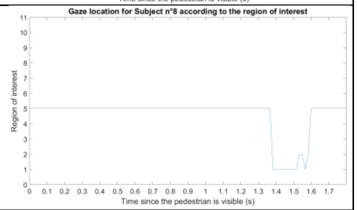
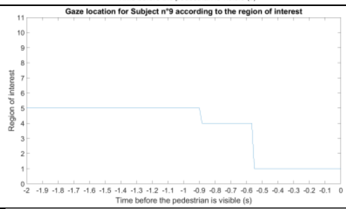
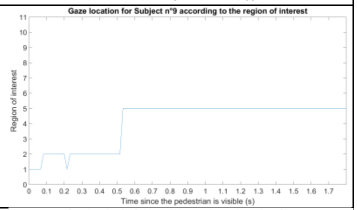
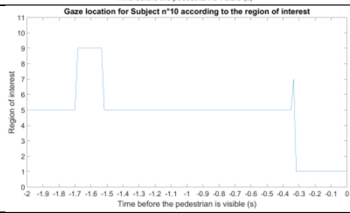
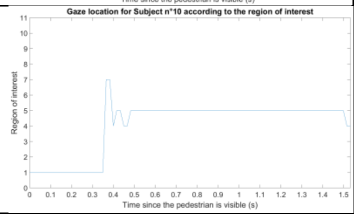
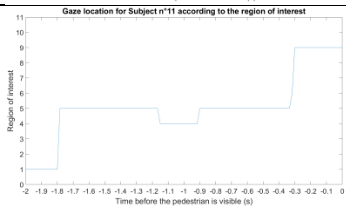
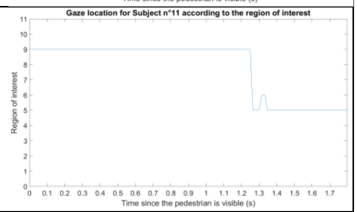
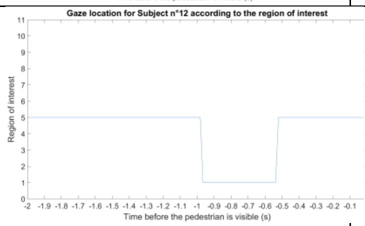
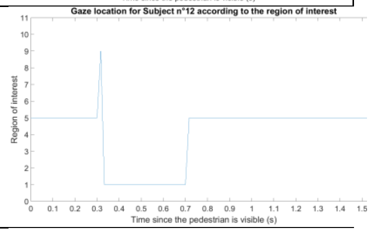
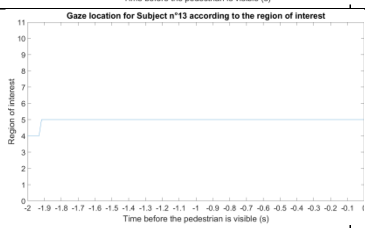
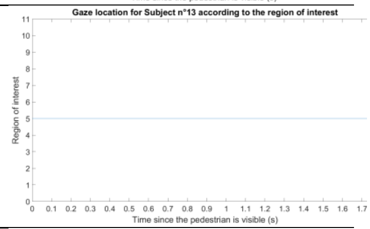
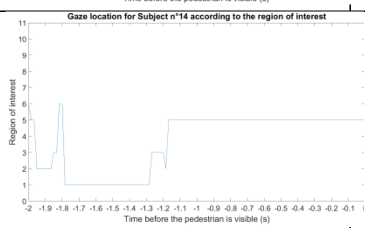
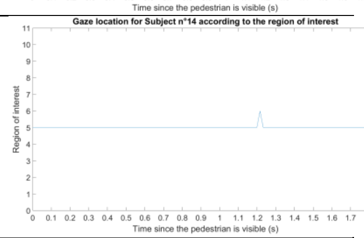

Acceleration and brake pedal stroke with the speed variation for Subject n° 19
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

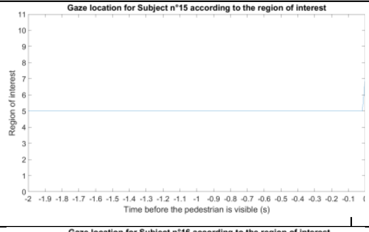
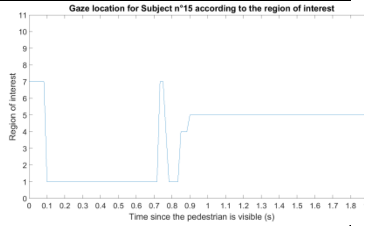
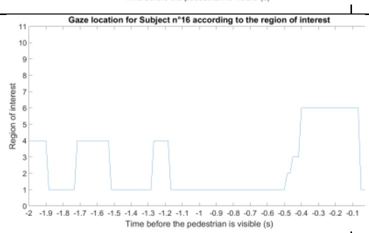
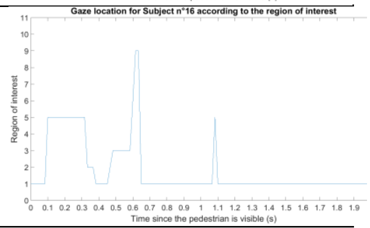
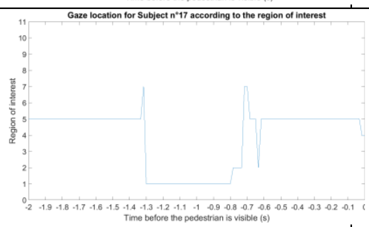
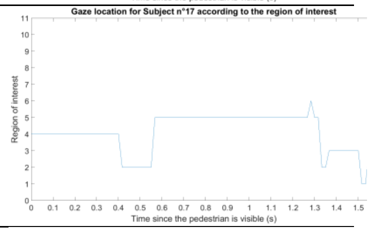
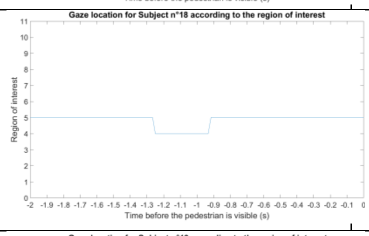
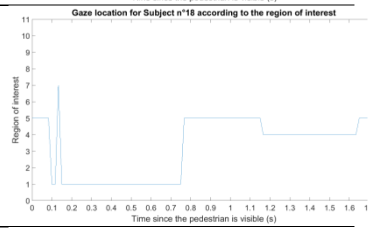
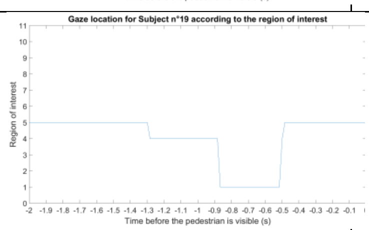
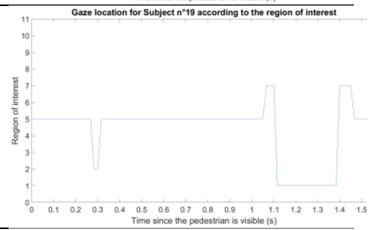
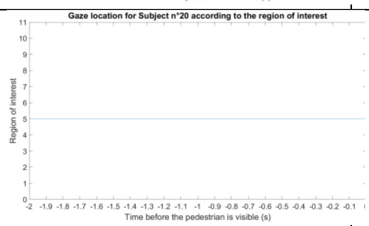
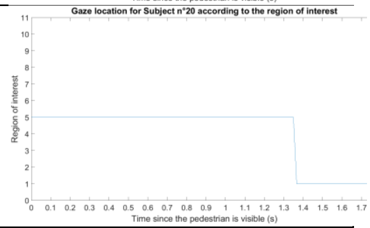

Acceleration and brake pedal stroke with the speed variation for Subject n° 20
Acceleration pedal
Braking pedal
LV speed (m/s)
Pedal stroke (%)
LV speed (m/s)
Time (s)

Discussion and conclusion

The chart below sums up the results obtained for the Pedestrian Crossing Nearside scenario.

		Time to release the gas pedal (s)	Time to begin to push the brake pedal (s)	Collision with pedestrian (s)	Gaze location from t=-2s to t=0s	Gaze location from t=0 to the impact or to the halt of the vehicle
Subject 1		0,83985	1,01563	1,52735		
Subject 2		Already released	0,90625	1,59375		
Subject 3		Already released	0,38672	No collision		
Subject 4		0,51171	0,73828	No collision		
Subject 5		0,25782	0,52344	No collision		
Subject 6	Pedestrian becomes visible t = 0s	0,09375	0,40234	No collision		

Subject 7		0,4414	0,61328	1,59375		
Subject 8		0,70312	0,89062	No collision		
Subject 9		0,19141	0,45313	No collision		
Subject 10		0,44531	0,93359	1,54297		
Subject 11		0,30468	0,46093	1,79687		
Subject 12		Already released	0,72656	1,5625		
Subject 13		0,3125	0,5625	No collision		
Subject 14		0,08594	0,35156	No collision		

Subject 15		0,17187	0,44922	No collision	 
Subject 16		0,45312	0,72265	No collision	 
Subject 17		0,22657	1,08985	1,57813	 
Subject 18		Already released	0,77344	No collision	 
Subject 19		0,80078	1,05469	1,56641	 
Subject 20		0,13281	0,28125	No collision	 

Among the 20 participants:

- Only 8 participants hit the Pedestrian for the Pedestrian Crossing Nearside scenario
- Nobody hit the Cyclist for the Cyclist Longitudinal scenario.

Participants' mean age is 31 years old.

Participants' time to release the gas pedal is 0.3741s in mean. Compared to others studies as described in Young & Stanton (2007), our values are close to those found by Warshawsky-Livne and Shinar (2002). In their study, they simulate a car-following situation in order to isolate variables as perception reaction time (RT) in condition where subject was informed of the nature of uncertainty. Perception reaction time is defined by the time “from the onset of the lights until the accelerator sensor detected the beginning of the release of the accelerator pedal”. They obtain values were between 0.32s to 0.42s and determine that RT increase significantly as uncertainty increase. Thus, as our measures include the time to fully release the gas pedal, a small additional time should be added to Warshawsky-Livne and Shinar values. On the contrary, if we make a comparison with Van der Hulst et al. (1999), values are very different. Reaction times were evaluated in following car situation depending of the deceleration of the lead car which is small and do not need fast reactions. Thus values obtained in their study are between 3 and 7s. As it is not an emergency situation, our values cannot be compared to their study.

Participants’ time to begin to depress the brake pedal is 0.66s in average. Schweitzer et al. (1995) measured the total braking response time (TBT), defined as the period from the onset of the brake lights of the leading vehicle to the contact with the brake pedal, in emergency situation by driving behind a leading vehicle. By varying the gap between vehicles, the total braking time increases in line. Our values seem to be in accordance with theirs TBT of 0.678 for naïve driving situation.

A comparison of time to begin to depressed brake pedal between our study (see figure 26 and 27) and data obtained from PCM database has to be considered with knowing some limitations. The method of considering the brake activation on our databases during accident reconstruction is not known. Moreover, our data come from an experiment on a driving simulator whereas data from our two databases (French EDA and German PCM) come from real accident situations. There might be a driving simulator effect. Last but not least, driving situations are completely different. Thus the configuration diversity brings a variability that is not constant contrary to the scenario in our study. Contrary to real accident where about half drivers activate brakes, people who have crash in P-CN scenario all activate brakes (figure 26). The brake activation in the driving simulator seems to be linear and similar to the figure 27. However as the sample of crash is small, this remains an assumption.

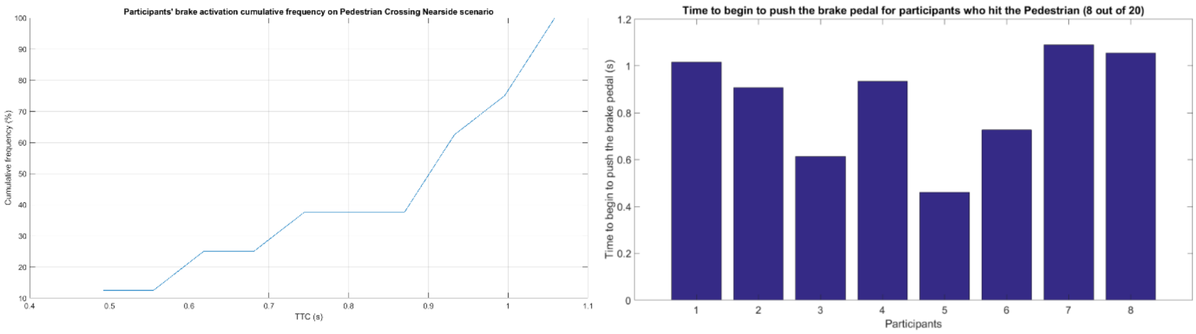


Figure 26: time to begin to depress the brake pedal for participants who hit the Pedestrian. Mean value is 0.8501s with a standard deviation of 0.2257.

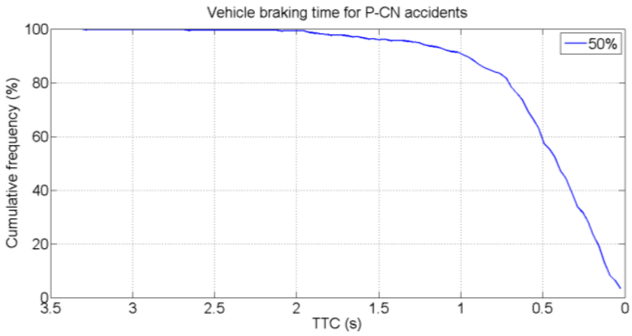


Figure 27: Brake activation Time To Collision (TTC) for Pedestrian Crossing Nearside cases from our accident databases

Conclusion

As most people avoid the accident in those 2 scenarios, a secondary task seems to be needed to increase collision occurrence.

Comparing drivers' reaction is not possible for the Cyclist Longitudinal scenario as people driving style are different in non-emergency situation. Thus comparing drivers' behavior is not possible.

Scenario order has no effect on drivers' reaction.

The total experiment duration for 1 person is about 1h30 in average. As the time needed to fill questionnaires is too long (about 40 minutes), the questionnaire should be reduced in order to be filled in less than 10 minutes. Indeed in the experiment with 180 participants we need to explain the secondary task and how work the Forward Collision Warning device with a guide. Moreover, it is better not to exceed a time experiment of 2 hours per participant as it will take more time to finish the experiment with all participants. Currently for a duration of 1h30 per participant, the experimental campaign is supposed to last 2 months and a half.

Gaze location measure will be improved. In this pilot study, some areas are defined and can indicate gaze position inside those areas. Then data gathered do not allow determining what is exactly seen during the driving session. For next study, data collection will be more precise. A video of the driving environment with location of the gaze during the driving session will be obtained. All data from the Facelab device will be matched with a frame from video of the driving situation using the following method. For each participant, the area where gaze location is analyzed is defined in the driving simulator environment. First, the limit of the image displayed by the projector is defined and delimited. Participant is asked to look those 4 corners to define and determine the size of this area in Facelab software. Then every eye tracker coordinates is matched to an image from the driving session according to time data. The matching will allow to get images of the driving with addition of the gaze precise location at each time step. Finally the set of images is compiled in order to have a video summarizing the driving session with addition of the gaze location as shown in figure 28. The location of gaze marker (red cross) is highlight in the picture by the white circle. Even if eye tracker data do not allow determining the perception of the VRU, it will still give the information of what can be seen during the driving.

Figure 28: example of gaze location method improved for next study.

B. Main experiment questionnaire

Sujet n°   Date :   Heure de passage :

Renseignements (au début de l'expérimentation)

Veuillez compléter les questionnaires suivants. Vos réponses resteront confidentielles et votre identité ne sera en aucun cas divulguée.

Age : ____________________
Sexe: Homme   Femme
Poids : ____________________
Taille: ____________________
Êtes-vous   Droitier   Gaucher

Portez-vous un dispositif de correction de la vue ?
Oui   Non
Si oui lesquels ? ___________________________

A votre connaissance, avez-vous des troubles du sommeil:
Oui   Non
A votre connaissance, avez-vous des troubles visuels :
Oui   Non
A votre connaissance, avez-vous des troubles moteurs :
Oui   Non
A votre connaissance, avez-vous des troubles auditifs :
Oui   Non

Nombre d'années de conduite : ____________________
Dernière fois que vous avez conduit : ____________________
Nombre de kilomètre que vous conduisez par semaine : ____________________
Fréquence de conduite par semaine :
1 jour   2-3 jour   4-5 jour   Plus de 5 jours
Quel type de conducteur pensez-vous être ?
Passif   Agressif   Prudent   Aventurier
A quelle heure avez-vous pris votre dernier café ou boisson caféinée (e.g. red bull)?______________
Avez-vous bu de l'alcool la nuit dernière ? Si oui, combien de verre(s) ? ____________________
Avez-vous dormi moins de 5 heures la nuit dernière ? ____________________

Avez-vous un avertisseur de collision frontale dans votre voiture ? ____________________
Avez-vous un système de freinage d'urgence automatique dans votre voiture ?___________________
Depuis combien d'années conduisez-vous votre voiture ? ____________________
Pensez-vous qu'un système vous prévenant quand vous pourriez percuter un piéton ou un cycliste pourrait vous être utile ? ____________________
Pensez-vous qu'un système déclenchant un freinage automatique quand vous pourriez percuter un piéton ou un cycliste pourrait vous être utile ? ____________________
Quel est la marque et le modèle de véhicule que vous conduisez habituellement ? _________________

Sujet n° Date : Heure de passage :

Karolinska Sleepiness Scale test (au début de l'expérimentation)

Niveau de somnolence en ce moment (Entourez votre réponse)
1 = vraiment très éveillé
2 = très éveillé
3 = éveillé
4 = assez éveillé
5 = ni éveillé ni somnolent
6 = signes de somnolence
7 = somnolent, mais reste éveillé sans effort
8 = somnolent, efforts nécessaires pour rester éveillé
9 = très somnolent luttant contre le sommeil

Scénario 1 : ________________
Pensez-vous que l'avertisseur de collision frontale a été utile ? Oui Non
Pourquoi (timing, contenu du message, commodité) ?_______________________________________

____

____

____

Scénario 2 :_________________
Pensez-vous que l'avertisseur de collision frontale a été utile ? Oui Non
Pourquoi (timing, contenu du message, commodité) ?_______________________________________

____

____

____

La tâche secondaire vous a-t-elle gênée ?
- Dans le scénario 1 : ____

____

____

____

- Dans le scénario 2 : ____

____

____

____

Sujet n° Date : Heure de passage :

Karolinska Sleepiness Scale test (à la fin de l'expérimentation)

Niveau de somnolence en ce moment (Entourez votre réponse)

1 = vraiment très éveillé
2 = très éveillé
3 = éveillé
4 = assez éveillé
5 = ni éveillé ni somnolent
6 = signes de somnolence
7 = somnolent, mais reste éveillé sans effort
8 = somnolent, efforts nécessaires pour rester éveillé
9 = très somnolent luttant contre le sommeil

C. Ethical approval

DEMANDE D'AVIS AU CERB

NOM DE L'ETUDE

Estimation des bénéfices apportés en sécurité routière par des avertisseurs de collision frontale pour les piétons et les cyclistes en Europe et sensibilité de ces systèmes.

(VRU-SIM)

Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (**IFSTTAR**)

Organisme demandeur : IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux).

Laboratoire Mécanismes d'Accidents (LMA)

Personnel IFSTTAR impliqué : Thierry Serre, François Char, Daniel Ndiaye, Stéphane Aillerie, Isabelle Aillerie

Si cette recherche relevait des dispositions du code de la santé publique relatives aux recherches impliquant la personne humaine au sens de l'article L.1121-1 du code de la santé publique, un dossier « dans les formes » serait rédigé.

I - IDENTITE DU DIRECTEUR DE LA RECHERCHE QUALIFIE

Nom : Serre

Prénom : Thierry

Adresse professionnelle : IFSTTAR/LMA, Chemin de la Croix-blanche, 13300 Salon de Provence

Titres et grade : docteur et HDR (habilité à diriger des recherche)

Fonctions : directeur de recherche, directeur adjoint du LMA

Téléphone du laboratoire : 04 90 56 86 30 télécopie : 04 90 56 25 51

Nom du directeur : Catherine Berthelon

Contrat financé par : Toyota TME

Intitulé : Estimation des bénéfices apportés en sécurité routière par des avertisseurs de collision frontale pour les piétons et les cyclistes en Europe et sensibilité de ces systèmes.

Septembre 2017

Identité du promoteur : Institut français des sciences et technologies des transports, de l'aménagement et des réseaux – Laboratoire Mécanismes d'Accident

Nom : Mme Jacquot-Guimbal

II - IDENTITE ET QUALITE DU PERSONNEL IMPLIQUE DANS LA RECHERCHE

Nom, prénom	**Titres, fonctions**	**Rôle dans la recherche**
Thierry Serre	Directeur de Recherche	Coordination et direction de la recherche
Stéphane Aillerie	Technicien	Création des images pour le simulateur
Isabelle Aillerie	Ingénieur de Recherche	Responsable simulateur
Daniel Ndiaye	Ingénieur d'études	Informatique et création des images
François Char	Doctorant	Passations expérimentales Traitement des données

Estimation des bénéfices apportés en sécurité routière par des avertisseurs de collision frontale pour les piétons et les cyclistes en Europe et sensibilité de ces systèmes.

Objectifs

De nombreux modules sont développés dans l'optique de détecter la présence de piétons ou de cyclistes sur la route afin d'avertir les conducteurs pour éviter une collision avec ces usagers vulnérables par un freinage ou une manœuvre d'évitement. Ces modules sont principalement basés sur une analyse en temps réel de la scène par l'intermédiaire de capteurs tel que des caméras. Un traitement d'images est alors utilisé pour identifier de potentielles collisions avec des piétons ou des cyclistes. Ce type de modules a très peu été testé sur des cas d'accidents réels, faisant ainsi apparaître la nécessité d'une évaluation de ces modules pour la sécurité routière.

L'objectif de cette expérimentation est d'étudier grâce à un simulateur de conduite les réactions de conducteurs face à un avertisseur de collision frontale dans des situations d'accidents réelles.

Les résultats de cette expérimentation vont être réintroduits dans des cas d'accidents réels pour estimer les bénéfices de ce type de modules pour la sécurité routière.

Méthode

Scénarios et simulateur de conduite

Ce travail s'effectuera à l'aide du simulateur de conduite dont dispose le Laboratoire Mécanismes d'Accidents de Salon de Provence (voir Figure 1 et l'Annexe pour une description plus détaillée).

Figure 1: Simulateur de conduite utilisé pour l'expérimentation.

Les personnes participant à la recherche conduiront le simulateur de conduite à base fixe dans des conditions proches de la conduite réelle. Ils seront alors confrontés à une situation inattendue et dangereuse puisqu'un piéton ou un cycliste va se trouver sur la trajectoire du véhicule conduit par la personne (Figure 2). 8 scénarios seront créés: 4 scénarios Piétons et 4 Cycliste (voir Figure 3). Les scénarios Piétons et Cycliste sont basés sur les mêmes configurations d'accidents :

- « Crossing Nearside » : un usager vulnérable arrivera du côté le plus proche de la route et traversera la route devant le véhicule.
- « Crossing Farside » : un usager vulnérable va traverser la route devant le véhicule en arrivant du côté opposé à la voie de circulation du véhicule.
- « Longitudinal » : un usager vulnérable va dans le même sens de circulation que le véhicule et une collision entre les deux usagers de la route peut survenir.
- « Turning Left » : un usager vulnérable traversera la route alors que la personne effectuera une manœuvre de tourne à gauche.

Figure 2: Exemple de l’apparence visuelle d’un scénario

Pedestrian				Cyclist			
Crossing Nearside	Crossing Farside	Longitudinal	Turning	Crossing Nearside	Crossing Farside	Longitudinal	Turning

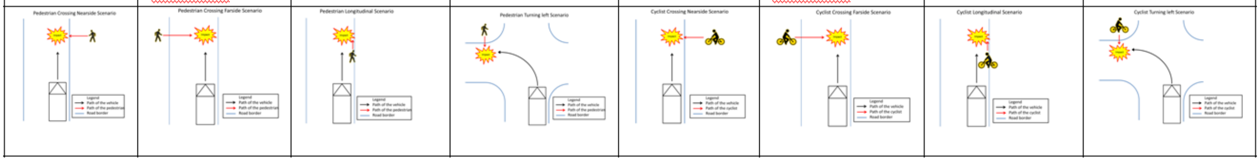


Figure 3: Scénarios sur simulateur

Pendant les expérimentations, toutes les personnes seront amenées à effectuer deux scénarios différents (1 scénario Piéton et 1 Cycliste) dans un ordre différent et les scénarios ne pourront pas être du même type (par exemple, si le premier scénario est un Piéton « Crossing Nearside », alors le scénario suivant ne pourra pas être un Cycliste « Crossing Nearside »). La moitié d’entre eux commenceront avec un scénario piéton et l’autre moitié avec un scénario cycliste.

Pendant chaque session de conduite qui durera environ 5 minutes, on leur demandera de suivre un chemin prédéfini dans un circuit fermé en environnement urbain avec du trafic. Cela les conduira à une zone potentielle de collision avec un usager vulnérable. Un usager vulnérable (Piéton ou Cycliste) apparaîtra sur le chemin du véhicule, de manière à ce que le module se déclenche et alerte le conducteur quelques secondes avant une potentielle collision (Figure 2). Au début de la session expérimentale, un guide expliquant le fonctionnement de l’avertisseur de collision frontale sera remis aux personnes prenant part à la recherche.

Différents temps de déclenchement de l’avertisseur de collision frontal seront évalués, 2 secondes et 1,7 seconde avant la collision (Time To Collision = TTC) afin de déterminer le meilleur moment pour déclencher le signal d’avertissement. Il s’agit d’un avertisseur audio-visuel, le signal audio est une alarme tandis que le signal visuel prendra la forme de l’apparition du message « FREINEZ » sur l’écran du simulateur. La position exacte du message visuel est encore à définir.

L’expérimentation est planifiée pour 180 sujets effectuant chacun 2 scénarios (1 Piéton et 1 Cycliste).

Mesures

Chaque personne expérimentera 2 scenarios différents pour évaluer sa réaction face à un avertisseur de collision frontale en fonction de différents types d'usagers vulnérables.

Leurs réactions seront évaluées grâce aux données produites telles que le temps mis pour relâcher la pédale d'accélération, le temps de freinage, la position du regard et la durée où le regard est resté sur une zone d'intérêt, l'angle du volant et leurs impressions subjectives sur le module via un questionnaire.

La position du regard sera mesurée via le module "FaceLab" (https://www.eyecomtec.com/3132-faceLAB) (Figure 4). A cette fin, une étape de calibration est requise pour enregistrer précisément les positions du regard pendant la conduite et également pour s'assurer des temps mis pour trouver quel signal sonore est émis (l'alerte), pour comprendre ce signal, pour regarder à nouveau la route et pour réagir. Durant chaque étape précédemment décrite, la position du regard dans des zones d'intérêts (route, tableau de bord, etc.) est enregistrée

La calibration de FaceLab pour chaque participant se fait de la façon suivante:

- vérifier le visage des participants pour s'assurer que l'enregistrement des données soit possible (pas de port de lunettes, pas de cheveux longs masquant le visage, etc.).

- localiser les yeux de chaque participant manuellement sur le logiciel et acquérir un certain nombre d'échantillons de l'œil (ouvert et fermé).

- calibrer la position de la pupille par l'acquisition de la position de l'œil et son orientation. Pour ce faire, les participants regarderont des cibles prédéfinies de manière à pouvoir avoir la localisation précise du regard.

- répéter l'opération pour l'autre œil.

Figure 4: le module "FaceLab"

Tâche secondaire

Pendant l'expérimentation, on demandera aux personnes de bien vouloir effectuer une tâche secondaire. Comme la tâche secondaire n'est pas encore définie à ce stade de la rédaction du présent document, une discussion avec TME est nécessaire. A titre d'exemple, une tâche qui pourrait être utilisée pour cette expérimentation sera décrite ici (Figure 5). La tâche suivante a été développée pour le projet européen HASTE (Jamson&Merat, 2005). Elle consiste en une matrice 4x4 constituée de flèches projetée sur un écran adjacent aux écrans sur lesquels sont projetées les images du simulateur de conduite. Les participants devront localiser une flèche cible (pointant vers le haut) parmi tous les autres distracteurs (toutes les autres flèches pointent ailleurs que vers le haut). La réponse qu'auront à fournir les participants a été adaptée par Kountouriotis et al (2016), consistant en une réponse orale de la part des personnes participant à l'expérimentation qui indiquent la position de ladite flèche en donnant ses coordonnées.

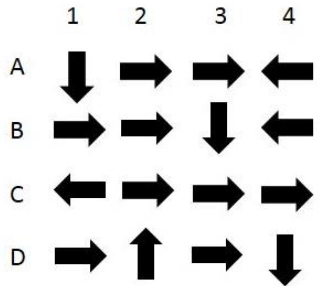


Figure 5: exemple de tâche secondaire

Echantillon des personnes participant à l'expérimentation

180 personnes seront recrutées par des annonces dans des journaux locaux. Elles auront toutes plus de 18 ans et devront être titulaires d'un permis de conduire valide.

140 Participants âgés de 25 à 55 ans

Il y aura 140 personnes ayant une expérience de conduite d'au moins 3 ans.

20 Participants âgés de 18 à 25 ans

Il y aura 20 personnes considérées comme jeunes conducteurs.

20 Participants âgés de 55 ans et plus

Il y aura 20 personnes considérées comme des conducteurs âgés.

Le recours à des personnes de 18 à 25 ans et de 55 ans et plus permettront de vérifier si l'âge est un facteur pouvant influencer l'efficacité de l'avertisseur de collision frontale (compréhension et réaction à ce signal).

La répartition globale de l'ensemble de ces personnes en fonction des 8 scénarios et des deux temps de déclenchement de l'avertisseur de collision frontale (déclenchement à 2 et 1,7 secondes avant choc) est indiquée dans la table 1.

	Piéton				Cycliste				Total
	Crossing Nearside	Crossing Farside	Longitudinal	Turning	Crossing Nearside	Crossing Farside	Longitudinal	Turning	

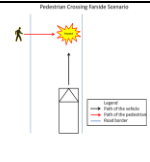
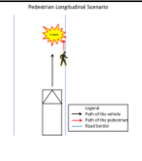
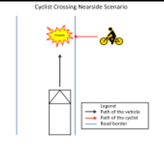
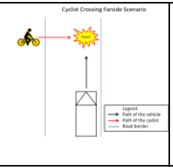
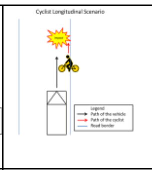
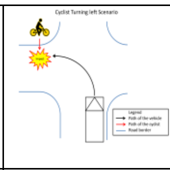
									
TTC 2s	10 + 20 jeunes + 20 âgés	10	10	10	10	10	10	10	120
2ndíteration	10	10	10	10	10 + 20 jeunes + 20 âgés	10	10	10	120
TTC 1.7s	20	0	0	0	0	0	0	0	20
2ndíteration	0	0	0	0	20	0	0	0	20
No FCW	5	5	5	5	5	5	5	5	40
2ndíteration	5	5	5	5	5	5	5	5	40
Total par scenario	90	30	30	30	90	30	30	30	360

Table 1: répartition des participants (le deuxième scénario est souligné)

L'expérimentation doit commencer le 1er octobre 2017.

Durée de l'expérimentation par personne participant à l'expérimentation

Chaque personne effectuera une session décrite ci-après pour un total de 2 heures.

- Accueil, formalité administrative (lecture du document de consentement, copie des documents d'identité) (10 minutes)
- Familiarisation avec un guide sur le fonctionnement de l'avertisseur de collision frontale (10 minutes)
- Familiarisation avec la tâche secondaire (10 minutes)
- Calibration du module Facelab (30 minutes)
- Familiarisation avec le simulateur de conduite (15 minutes)
- Expérimentation du 1er scénario (5 minutes)
- Pause (5 minutes)
- Expérimentation du 2ème scénario (5 minutes)
- Remplissage du questionnaire concernant les impressions au sujet de l'avertisseur (10 minutes)
- Débriefing et récupération (20 minutes)

Les participants ne seront équipés d'aucun système.

Analyse des données et leurs traitements

Les données obtenues par l'expérimentation vont permettre d'acquérir des connaissances qui permettront de comprendre ce qui suit. Après distraction des conducteurs pendant la conduite via une tâche secondaire, l'avertisseur de collision frontale se déclenche par l'émission d'un signal audio-visuel pour alerter le conducteur de l'imminence d'une collision avec un usager vulnérable. La réaction de la personne au module d'alerte est divisée en différentes phases du comportement du conducteur comme le montre la figure 6.

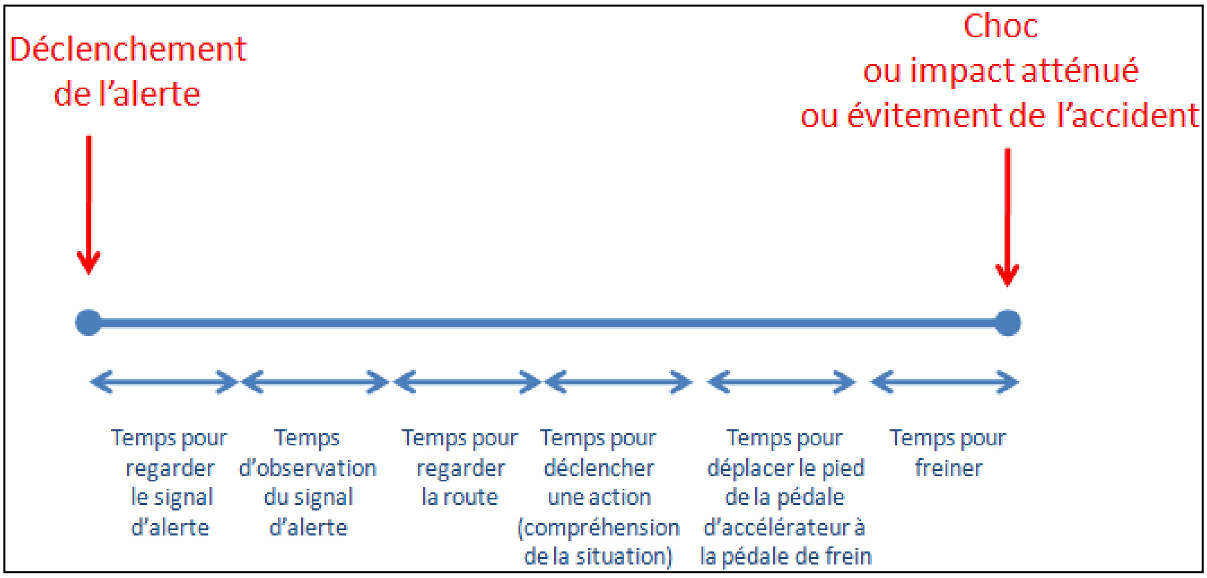


Figure 6: Différentes phases de la réaction du conducteur

Les variables mesurées

- Localisation du regard
- Temps mis pour relâcher la pédale d'accélération
- Temps mis pour activer le frein
- Angle du volant

Note : les données enregistrées sur simulateur pendant les expériences sont la propriété de l'IFSTTAR et ne seront accessibles qu'au personnel de l'IFSTTAR. Toyota ne disposera que des données anonymes analysées et moyennées sur l'ensemble des participants.

Annexe

Le dispositif expérimental

Le simulateur de l'IFSTTAR, situé à Salon de Provence, est un simulateur à base fixe. L'espace conducteur est composé d'un habitacle complet de véhicule. Les principales commandes sont opérationnelles (tableau de bord, pédalier, volant, commodo volant et central). Les organes de commande suivants ; volant, pédale d'accélérateur, pédale de frein, commodo volant et commodo central (contact, démarreur et interrupteur de frein à main) sont équipés de capteurs. Les indicateurs de vitesse et compte tour ainsi que les voyants du tableau de bord sont connectés. L'image de la scène routière est projetée à l'avant sur 3 écrans (1,80 m de largeur x 1.35 m de hauteur), un écran central situé face au conducteur et 2 écrans latéraux orientés à 50° (placés à 1.93 m de l'œil du conducteur), soit un champ visuel de 150° en horizontal et 40° en vertical, chaque écran à une résolution de 1280 x 1024 pixels. Des écrans d'ordinateur, positionnés sur les portes latérales du véhicule, peuvent se déplier et permettent de projeter les images de la scène arrière sur les rétroviseurs extérieurs.

Un son en quadriphonie est diffusé dans la cabine – bruits internes au véhicule (moteur, roulement, démarreur) et bruits externes spatialisés du trafic. Le simulateur est composé d'un module graphique SIM2 permettant la visualisation en temps réel des scènes visuelles et des scénarii routiers. La gestion du trafic routier se fait par un logiciel nommé Archisim.

INFORMATIONS DONNEES AUX PERSONNES PARTICIPANT A L'EXPERIMENTATION ET MODALITES DE DELIVRANCE DE CETTE INFORMATION

Titre de la recherche : Evaluation d'un module d'aide à la conduite

Identité du promoteur : Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (IFSTTAR) – Laboratoire Mécanismes d'Accidents, représenté par Mme Jacquot Guimbal.
Adresse : Chemin de la Croix-Blanche, 13300 Salon de Provence.

Financeur : TOYOTA ME

Il vous est proposé de participer à une recherche qui porte sur l'évaluation d'une aide à la conduite dont L'Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (IFSTTAR) est promoteur. La durée de l'expérimentation liée à cette recherche sera de deux heures maximum. Les résultats globaux de cette expérimentation seront fournis à Toyota ME qui finance cette recherche.

Cette notice d'information vous est remise pour que vous puissiez prendre connaissance du projet auquel nous vous proposons de participer. Elle a pour but de vous permettre d'exprimer votre volonté en toute connaissance de cause. Vous disposez d'une semaine de réflexion pour faire votre choix. Si vous êtes d'accord pour prendre part à cette recherche, merci de bien vouloir donner votre consentement en nous rapportant signés le formulaire de consentement.

Les informations relatives à l'objectif de la recherche ne vous seront pas communiquées avant la fin de l'expérimentation afin d'éviter toutes influences sur les résultats.

Vous serez amené à conduire le simulateur de l'IFSTTAR. Des caméras situées dans le simulateur enregistreront vos réactions sur chacun des scénarios. Après une phase de familiarisation avec le simulateur de conduite, votre tâche sera de conduire dans le simulateur en suivant un itinéraire prédéfini sur plusieurs scénarios de conduite. Avant et après la conduite, des questionnaires seront à compléter. Une fois l'ensemble des scénarios effectués et après avoir fini de remplir les questionnaires, une phase de débriefing/récupération aura lieu afin de vous expliquer l'objectif de la recherche et de vous permettre de récupérer après cette passation expérimentale.

L'IFSTTAR a souscrit auprès d'Axa France Iard une assurance de responsabilité civile couvrant les conséquences dommageables éventuelles que vous pourriez subir du fait de votre participation au projet de recherche.

Votre participation d'une durée maximale de deux heures s'inscrit dans une étude s'étendant jusqu'en mars 2018. Vous percevrez une indemnité forfaitaire de 40€ en compensation des contraintes et des frais générés par votre participation à cette recherche.

Les résultats individuels et les différentes données qui vous sont personnelles resteront strictement confidentiels. Seul M. Thierry Serre, ainsi que les personnes travaillant sous son contrôle auront accès à ces données. Elles ne feront pas l'objet d'échanges ou de valorisation sans que vous en ayez été informé et ayez donné votre accord. Conformément à la loi n°78-17 du 6 Janvier 1978, relative à l'informatique, aux fichiers et aux libertés, modifiée par la loi n° 2004-801 du 6 août 2004 relative à la protection des personnes physiques à l'égard des traitements de données à caractère personnel (article 39), vous avez le droit d'accéder, à tout moment, aux données vous concernant recueillies dans cette étude en contactant M. Thierry Serre à l'IFSTTAR, 304 chemin de la croix blanche, 13300 Salon de Provence au 0490568653 ou par mail : thierry.serre@ifsttar.fr.Vous disposez également d'un droit de rectification et d'un droit d'opposition à la transmission des données couvertes par le secret professionnel susceptibles d'être utilisées dans le cadre de cette recherche et de faire l'objet d'un traitement informatique.

FORMULAIRE DE CONSENTEMENT LIBRE ET ÉCLAIRÉ

(Établi en deux exemplaires, un pour le participant, un pour le directeur de la recherche)

Titre de l'étude : Evaluation d'un module d'aide à la conduite

De M, Mme.. (Nom, Prénom)
Adresse :
……………………..

J'ai été invité-e à participer à une étude réalisée par l'IFSTTAR concernant un module d'aide à la conduite dont les résultats de cette expérience, seront fournis à Toyota ME. J'ai été libre d'accepter ou de refuser.

J'ai reçu et compris les informations suivantes : je serai amené-e à conduire le simulateur de conduite et à participer à cette étude pendant 2h maximum.

Le but de cette étude est de recueillir des informations sur une aide à la conduite. **Les instructions détaillées** concernant le déroulement de l'étude me seront fournies lors de celle-ci par les personnes qui la mettront en œuvre**. J'ai reçu une réponse satisfaisante à toutes les questions que j'ai pu poser librement à propos de celle-ci.**

J'accepte de participer à cette étude dans les conditions précisées ci-dessus.

Mon consentement ne décharge pas les organisateurs de l'étude de leurs responsabilités. Je conserve tous mes droits garantis par la loi. Si je le désire, je suis libre à tout moment d'arrêter ma participation, j'en informerai alors le responsable de l'étude, son collaborateur ou toute autre personne avec qui je serai amené à être en contact au cours de cette recherche.

Les données me concernant resteront strictement confidentielles. Je n'autorise leur consultation et leur traitement informatique que par des personnes qui collaborent à l'étude. J'ai bien noté que le droit d'accès, prévu par loi n°78-17 du 6 Janvier 1978, relative à l'informatique, aux fichiers et aux libertés, modifiée par la loi n° 2004-801 du 6 août 2004 relative à la protection des personnes physiques à l'égard des traitements de données à caractère personnel (article 39), est applicable à tout moment. Je pourrai demander toute information complémentaire aux personnes avec lesquelles je serai amené à être en contact au cours de cette recherche, et notamment à Monsieur Thierry Serre, IFSTTAR, 304 Chemin de la Croix Blanche, 13300 Salon de Provence, téléphone : 04 90 56 86 30, mail : thierry.serre@ifsttar.fr.

Je percevrai une indemnité de 40€, en compensation des contraintes et frais générés par ma participation à cette recherche.

Signature du participant

Le ………………………….

D. Driving simulator main experiment results

TR-PR scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S1	55	F	1	Yes	-1,141	-0,922	Y	45 10 16 8	45 10 16	do the 2nd task until accident	
S3	26	F	1	No	-1,148	-0,789	Y	45 10 16 8	35 .. 16	do the 2nd task until the car stops	
S4	55	H	1	No	No gas release	<-8s	Y	45 10 16 8	45 10	try to continue the task during turning until theoretical impact	
S5	22	H	1	No	-1,199	-0,8593	Y	45 10 16 8	45 10 16 8	do the 2nd task until the car stops	
S6	55	H	1	No	-1,164	-0,746	Y	45 10 16 8	45 10 I don't know 8	do the 2nd task until the car stops	
S7	41	H	1	No	-1,043	-0,848	Y	45 10 16 8	45 10 16 8	do the 2nd task until the car stops	
S8	55	H	1	No	-1,243	-0,984	Y	45 10 16 8	45 10 16 ..	do the 2nd task until the car stops	
S9	55	H	1	No	-0,321	-0,063	undefined	45 10 16 8	record failure	do the 2nd task until the pedestrian overtaking	
S10	36	F	1	No	-1,137	-0,617	Y	45 10 16 8	45 10 16 8	do the 2nd until the impact	
S11	55	H	1	No	-2,078	-0,805	Y	45 10 16 8	45 10 16 8	do the 2nd task until the car stops	
S22	31	H	2	No	-2,16	-1,563	Y	45 10 16 8	45 10 16 8	do the 2nd task until the car stops	
S45	55	H	2	No	-1,191	-0,984	Y	45 10 16 8	45 10 16 8	do the 2nd task to the end; just after the task audio warning, speed is highly decreased	
S46	33	H	2	No	-1,055	-0,875	Y	45 10 16 8	45 10 16 8	do the 2nd task until the car stops	
S48	40	H	2	No	-2	-0,972	Y	45 10 16 8	40 .. 18 8	do the 2nd task until the car stops	

FCW 2s												
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S66	48	H	2	No	-1,34	-0,941	Y	45 10 16 8	45 10 16 8	do the 2nd task until the end; task ends before FCW trigger	I brake before the FCW is triggered	FCW perceived
S67	38	H	2	No	-1,336	-1,07	Y	45 10 16 8	.. 82	try to do the 2nd task; low rate of correct answers during the training	FCW confirm the manoeuver	audio FCW perceived, audio FCW is not distinctive enough from the environment
S68	46	F	2	No	-3,902	-0,86	Y	45 10 16 8	45 10	do the 2nd task until FCW triggers, then no more response	I focus on the driving rather than on the 2nd task	
S69	25	F	2	No	-2,141	-1,301	Y	45 10 16 8	45 10 16 I forget the last one	do the 2nd task entirely	I brake at FCW trigger or just a little after	no perception benefit
S70	54	F	2	No	-1,383	-0,762	Y	45 10 16 8	45 10	do the 2nd task until FCW triggers	FCW confirms the manoeuver but is not responsible of the braking	FCW should be triggered earlier when danger can be perceived
S71	37	H	2	No	-1,875	-1,242	Y	45 10 16 8	45 10 16 8	do the 2nd task entirely	FCW confirm the braking and prioritize task (driving then 2nd task)	audio FCW perceived first then visual
S72	51	H	2	No	-1,34	-0,801	Y	45 10 16 8	45 10 16 I miss one	do the task entirely	FCW confirm the situation, I think I could stop even without FCW	audio FCW is more perceived than visual
S73	45	F	2	No	-1,539	-1,078	Y	45 10 16 8	45 10 16 ..	do the 2nd task until FCW triggers	FCW triggers the braking	audio FCW perceived
S74	43	H	2	No	-1,477	-0,883	Y	45 10 16 8	45 10 16 ..	do the 2nd task until FCW triggers	reaction at the same time of FCW trigger	no benefit or adverse effect of FCW
S116	48	F	1	No	<-10s	<-8s	Y	45 10 16 8	40 10 I don't the remaining	do the task until FCW triggers	don't remember if brake before, during or after FCW trigger	maybe perceived visual FCW (not sure), audio FCW not perceived (a priori)
S117	33	F	1	No	-1,184	-0,922	Y	45 10 16 8	45 10 16	do the task until FCW triggers	maybe brake at the same time of FCW trigger	
S118	25	F	1	No	-1,723	-1,203	Y	45 10 16 8	45 10 16	do the 2nd task until FCW triggers	brake at the same time of FCW trigger; FCW confirm the braking	audio FCW is perceived
S119	47	H	1	No	-1,195	-0,922	Y	45 10 16 8	45 10 16	do the 2nd task until FCW triggers	FCW is useful to react	a signal is perceived (don't remember)
S120	37	H	1	No	-1,281	-0,898	Y	45 10 16 8	45 10	do the 2nd task until FCW triggers	FCW perceived as useful	audio FCW perceived, visual FCW is perceived at the end of the scenario
S121	25	H	1	No	<-9s	-1,082	Y	45 10 16 8	45 10 16 ..	do the task until FCW triggers	FCW has triggered the braking	only audio FCW perceived, FCW is found useful
S122	24	H	1	No	-1,484	-0,93	Y	45 10 16 8	85 10 .. 8	do the task entirely until FCW trigger	brake potentially after FCW (not sure)	audio and visual FCW perceived at the same level

FCW 1.7s												
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S86	50	F	2	No	-0,926	-0,641	Y	45 10 16 8	45 10 16 8	do the 2nd task entirely	reaction at the same time of FCW trigger or just after	visual FCW perceived
S87	54	F	2	No	No release	<-4s	Y	45 10 16 8	45 .. 16 8	do the 2nd task entirely; steering manoeuver to avoid	trigger steering manoeuver before FCW trigger	visual FCW is perceived lately
S88	55	H	2	No	-1,121	-0,828	Y	45 10 16 8	45 10 16	do the 2nd task until FCW triggers	braking at the same time FCW triggers; FCW confirm the braking and the understanding of the situation	visual FCW is perceived and audio not
S90	55	H	2	No	-1,102	-0,801	Y	45 10 16 8	45 18 I miss the last one I think (record failure)	inside cam record failure	braking is triggered by FCW signal	visual FCW is perceived and audio not
S91	44	F	2	No	-1,102	-0,704	Y	45 10 16 8	45 10 16 8	do the 2nd task entirely	braking before the FCW	visual FCW is perceived
S92	44	H	2	No	-1,621	-1,18	Y	45 10 16 8	45 10 16 I don't remember the last number	do the 2nd task entirely	FCW confirm the braking manoeuver	audio FCW is perceived then visual FCW when stopped
S93	44	H	2	No	-1,281	-0,82	Y	45 10 16 8	about 50 10 16 8	do the 2nd task entirely	FCW has no effect on reaction and is not responsible of the braking	audio and visual FCW perceived
S94	49	F	2	Yes	-1,058	-0,687	Y	45 10 16 8	45 10 16 8	do the 2nd task entirely	brakes are triggered before or at the same moment of FCW trigger	visual FCW is perceived and not audio
S95	52	H	2	No	-0,942	-0,641	Y	45 10 16 8	45 10 16	do the 2nd task until FCW triggers	brake at the same time FCW triggers or just after	visual FCW perceived
S96	51	H	1	No	-1,102	-0,703	Y	45 10 16 8	45 10 heu ..	do the 2nd task until FCW triggers	I brake just a little after FCW	audio and visual FCW perceived, audio is a little too aggressive
S97	29	H	1	No	-1,406	-1,039	Y	45 10 16 8	heu 10 16	do the 2nd task	I brake before FCW; no effect of FCW according participant; FCW annoys for 2nd task answer	FCW perceived
S99	40	F	1	No	-1,164	-0,926	Y	45 10 16 8	45 10 16 ..	do the 2nd task until FCW triggers	reaction at the same time of FCW trigger	visual FCW perceived then audio; no benefit or adverse effect of FCW
S100	41	F	1	No	-1,258	-1	Y	45 10 16 8	45 10 16 8	do the 2nd task entirely before FCW triggers	braking is triggered after FCW signal	audio FCW better perceived than visual and is responsible of braking
S101	41	F	1	No	-1,172	-0,968	Y	45 10 16 8	45 10	do the 2nd task until FCW triggers	react at the same time of FCW trigger or just a little after (not sure)	audio FCW not perceived, visual FCW perceived
S103	36	F	1	Yes	-0,946	-0,555	Y	45 10 16 8	45 10	do the 2nd task until the impact	brake at the same time FCW triggers	audio and visual FCW perceived; FCW has disturbed because of its trigger after the turning
S104	55	H	1	No	-1,316	-1,129	Y	45 10 16 8	45 10 16 ..	do the 2nd task until FCW triggers	I brake before FCW trigger	audio and visual FCW perceived; FCW is not annoying
S106	39	F	1	No	-1,14	-0,882	Y	45 10 16 8	45 10 16	do the 2nd task until FCW triggers		audio and visual FCW are perceived at the end of the braking

TL-CR scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S1	55	F	2	No	NA	NA	Y	20 10 12 24	20 heu 12 heu	no emergency situation	
S3	26	F	2	No	NA	NA	Y	20 10 12 24	20 10 .. I don't know	no emergency situation	
S4	55	H	2	No	NA	NA	Y	20 10 12 24	20 40 12 48	no emergency situation	
S5	22	H	2	No	NA	NA	Y	20 10 12 24	20 10 12 24	no emergency situation	
S6	55	F	2	No	NA	NA	undefined	20 10 12 24	record failure	no emergency situation	
S7	41	H	2	No	NA	NA	Y	20 10 12 24	20 10 12 24	no emergency situation	
S8	55	H	2	No	NA	NA	undefined	20 10 12 24	record failure	no emergency situation	
S9	55	H	2	No	NA	NA	undefined	20 10 12 24	record failure	no emergency situation	
S10	36	F	2	No	NA	NA	Y	20 10 12 24	20 10 heu I don't know	no emergency situation	
S11	55	H	2	No	NA	NA	Y	20 10 12 24	20 10 12 I don't know	no emergency situation	

NA: Not analyzed (no emergency reaction)

TL-PL scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S22	31	H	1	No	-1,695	-1,446	Y	36 20 5 7	36 20 5 7	do the 2nd task until stop	
S37	27	H	1	No	<-9s	-1,367	Y	36 20 5 7	37 20 1 7	do the 2nd task until stop	
S38	28	H	1	No	-2,657	-1,836	Y	36 20 5 7	36 20 5 28	do the 2nd entirely	
S42	44	F	1	No	-2,011	-1,628	Y	36 20 5 7	28 24	do the 2nd task until stop	
S43	35	F	1	No	-1,258	-1,082	Y	36 20 5 7	36 20 1 ..	do the 2nd task	
S44	30	F	1	No	-2,965	-2,406	Y	36 20 5 7	28 9 5 I haven't heard 7	do the 2nd task entirely	
S45	55	H	1	No	-1,629	-1,375	Y	36 20 5 7	36 20 5 7	do the 2nd task entirely	
S46	33	H	1	No	-2,828	-2,528	Y	36 20 5 7	32 20	do the 2nd task until stop	
S47	37	H	1	No	-3,617	-2,96	Y	36 20 5 7	28 20 5 7	do the 2nd task entirely	
S48	40	H	1	No	-1,793	-1,574	Y	36 20 5 7	36 20 5 35	do the 2nd task entirely	
S61	49	H	2	No	-2,488	-1,254	Y	36 20 5 7	36 20 5 35	do the 2nd task entirely	
S62	24	F	2	No	-3,727	-2,809	Y	36 20 5 7	I don't have it (x5)	low rate of good answer during the training; try to do the 2nd task (thinking loud)	
S63	55	H	2	No	-2,485	-2,118	Y	36 20 5 7	36 20 5 35	do the 2nd task entirely	
S64	29	F	2	No	-3,726	-2,425	Y	36 20 5 7	I don't know 20 10 35	do the 2nd task entirely	

TL-PR scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S23	32	H	1	Yes	-1,117	-0,859	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	
S24	55	H	1	No	-2	-1,4	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	
S25	30	H	1	No	-2,101	-1,363	Y	14 35 15 27	14 45 15 27	do the 2nd task entirely	
S26	45	H	1	No	-2,285	-1,402	Y	14 35 15 27	14 35 21 I don't remember	do the 2nd task entirely	
S27	55	H	2	No	-2,238	-1,418	Y	14 35 15 27	14 35 .. 27	do the 2nd task entirely	
S28	34	H	2	No	-2,121	-1,582	Y	14 35 15 27	14 35 15 45	do the 2nd task entirely	
S29	28	H	2	No	-1,253	-0,957	Y	14 35 15 27	14 35 15 21	do the 2nd task entirely	
S30	25	H	2	No	-1,32	-1,02	Y	14 35 15 27	14 heu 42 not heard	do the 2nd task until the car stops	
S32	51	H	2	No	-2,039	-1,621	Y	14 35 15 27	14 35 15 21	do the 2nd task entirely	
S33	29	F	2	No	-2,14	-1,597	Y	14 35 15 27	14 20 15 27	do the 2nd task entirely	
S34	55	H	2	Yes	<-8s	-1,199	Y	14 35 15 27	14	do the 2nd task until the impact	
S35	55	H	2	No	-2,297	-1,418	Y	14 35 15 27	14 35 15 ..	do the 2nd task until the car stops	
S36	36	F	2	No	<-4s	-1,203	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	
S49	45	H	1	No	-2,093	-0,921	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	
S50	42	F	1	No	-2,082	-1,375	Y	14 35 15 27	14 35 15 45	do the 2nd task entirely	
S51	38	F	1	No	-1,5	-1,219	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	
S52	42	F	1	No	-1,261	-0,941	Y	14 35 15 27	14 35	do the 2nd task until the car stops	
S54	30	H	1	No	-1,164	-0,886	Y	14 35 15 27	14 35 15 45	do the 2nd task entirely	
S55	42	F	1	No	-1,543	-1,305	Y	14 35 15 27	14 35 21 63	do the 2nd task entirely	

FCW 2s												
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S116	48	F	2	No	-2,242	-1,66	Y	14 35 15 27	14 30 15 45	do the 2nd task entirely	don't remember if brake before during or after FCW trigger	audio + visual FCW perceived
S117	33	F	2	Yes	-1,121	-0,821	Y	14 35 15 27	14 .. 15 27	do the 2nd task entirely	brake after FCW trigger; FCW warns and allows to react even if it is too late	FCW audio and pedestrian are perceived at the same time
S118	25	F	2	No	-2,172	-1,188	Y	14 35 15 27	14 25	do the 2nd task until FCW triggers	brake after FCW triggers; FCW helps to react faster	audio FCW perceived
S119	47	H	2	Yes	-1,305	-1	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	FCW seems to be triggered too late but increase emergency degree	visual FCW perceived
S120	37	H	2	No	-1,297	-0,859	Y	14 35 15 27	14 35 21 I'm lost	do the 2nd task entirely	brake at the same time FCW triggers; FCW is a plus because confirms the chosen reaction	audio FCW perceived
S121	25	H	2	No	-1,691	-1,297	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	brake before FCW triggers; FCW confirm the brake decision	audio FCW perceived after handling the situation
S122	24	H	2	No	-1,961	-1,602	Y	14 35 15 27	14 35 heuu 27	do the task entirely	FCW potentially influences the reaction	audio FCW is perceived
S127	46	F	1	No	-2,262	-1,32	Y	14 35 15 27	14 35 15 45	do the 2nd task entirely	braking is triggered by FCW signal; FCW perceived as useful	audio then visual FCW perceived
S128	52	H	1	No	-1,461	-1,203	Y	14 35 15 27	14 35 15 45	do the 2nd task entirely	brake at the same time FCW triggers or just a little after, not annoying signal because is a plus	audio then visual FCW perceived
S129	39	F	1	No	-2,238	-1,277	partially	14 35 15 27	14	try to do the 2nd task but only give 1 answer before give up	brake before FCW triggers	audio + visual FCW perceived
S130	36	F	1	Yes	-2,715	-0,93	Y	14 35 15 27	14 35 15 ..	do the 2nd task until FCW triggers	brake at the same time FCW triggers or just after; no effect of FCW (no positive or negative)	visual FCW perceived, audio not perceived
S131	44	H	1	No	-1,93	-1,156	Y	14 35 15 27	14 45 15 .. I don't remember the 4th	do the 2nd task entirely	brake at the same time FCW triggers; FCW confirm and accentuate the braking	audio FCW perceived then visual after analysis
S132	49	H	1	No	-2,364	-1,098	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	no memory of if braking is before, during or after FCW trigger; FCW confirm the braking and accelerate the decision making	audio + visual FCW perceived
S133	37	H	1	No	-1,332	-1,035	Y	14 35 15 27	14 35 15 45	do the 2nd task entirely	no perception of FCW	no memories of FCW perception
S134	35	H	1	No	-1,609	-1,125	Y	14 35 15 27	14 35 15 27	do the 2nd task entirely	brake at the same time of FCW trigger; potential reaction to a signal; FCW is a priori useful	audio FCW perceived and visual not

P-L scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S23	32	H	2	No	-1,578	No braking	partially	5 3 8 4 0	5 3 0 not see all	glance back to road during task	
S24	55	H	2	No	-1,02	-0,496	Y	5 3 8 4 0	5 3 8 0	fully distracted, steers to avoid accident	FCW would have been useful to return to road
S25	30	H	2	No	-2,149	-1,801	partially	5 3 8 4 0	there was 5 0 8 4 in the batch	glance back to road during task	after the message "visual task", when going to look at the screen, I see the P and react
S26	45	H	2	No	-2,164	-1,926	N	5 3 8 4 0	3 4 0 I have forgot some	gaze is on the road and stay on the pedestrian when it appears, then the gaze goes to the 2nd task screen	I see the pedestrian at the end of the digit series
S49	45	H	2	Yes	No fully release	No braking	Y	5 3 8 4 0	5 3 8 4 0	Gaze completely focus on screen, no reaction to the situation, fully distracted	pedestrian is not seen, the work zone is not seen
S50	42	F	2	No	<-4s	-2,071	partially	5 3 8 4 0	record failure	glance back at the road at the beginning of the task	focus on the road rather on the 2nd task after seeing the pedestrian
S51	38	F	2	No	<-4s	-1,82	partially	5 3 8 4 0	3 8 4 0 I miss one	look at the 2nd task only after having braked	the pedestrian is seen in the corner of my eyes because something was moving
S52	42	F	2	Yes	-0,18	No braking	partially	5 3 8 4 0	no answer	look at the screen and see the pedestrian at the end of the 2nd task	
S54	30	H	2	Yes	-0,222	No braking	Y	5 3 8 4 0	5 3 8 4 0	look at the screen during the whole task and don't see the pedestrian, fully distracted	
S55	42	F	2	No	-3,18	-1,758	partially	5 3 8 4 0	i see 3 0 4	glance back at the road during the task	
S136	28	F	2	No	-2,289	-1,961	N	5 3 8 4 0	5 3 8 4 0	gaze is on the road until participant reacts	
S137	28	H	2	No	-1,199	-0,941	partially	5 3 8 4 0	5 8 4 0	glance back to the road during the 2nd task	choice to focus on driving rather than 2nd task
S138	54	H	2	No	-2,398	-2,136	N	5 3 8 4 0	5 3 8 4 0	gaze goes on the 2nd task screen only after braking; the braking is triggered during the pedestrian setting up; no effect of the 2nd task	surprising event even if more expectation about this second scenario; the pedestrian setting up is seen
S139	39	H	2	No	-2,316	-1,89	N	5 3 8 4 0	5 3 8 4 0	gaze says on the road until braking is triggered; pedestrian setting up is seen; no effect of the 2nd task	difficult to handle driving and the 2nd task; expect a pedestrian to appear suddenly => observation of all pedestrians and check behind the bus
S143	53	H	2	No	<-4s	-1,887	partially	5 3 8 4 0	5 8 4 0 one is missing	answer is not given at the end of the 2nd task but during the display progress; glance back at the road during the 2nd task	Expect something to happen during a 2nd task

FCW 2s												
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S76	27	H	1	No	-3,079	-2,625	Y	5 3 8 4 0	3 8 4 0		pedestrian is seen during the setting up, I react before FCW; FCW is scary and is annoying as the situation was well understood	FCW is perceived
S77	38	F	1	Yes	-1,563	-0,883	partially	5 3 8 4 0	5 4 0		visual FCW is disturbing, I rather prefer "react or directional arrow" as I was thinking to steer	FCW perceived
S78	43	H	1	Yes	-0,262	No braking	Y	5 3 8 4 0	I have not seen	eye tracker video gives little information	audio FCW allows to see the situation	audio FCW is perceived, visual FCW is not correctly perceived due to camera
S79	32	H	1	Yes	-2,175	-1,808	Y	5 3 8 4 0	5 8 I don't remember and 4 I think			no perception of FCW because focus on 2nd task and on the pedestrian
S80	45	F	1	Yes	<-4s	-1,477	partially	5 3 8 4 0	3 8 4 0	do the 2nd task entirely	reacts to audio FCW, steers and brakes (steering is realized to avoid pedestrian without noticing the opposite traffic)	audio FCW perceived
S81	47	H	1	No	-2,289	-1,836	partially	5 3 8 4 0	I don't have it	gaze comes back to the road just before the FCW triggers	pedestrian setting up is seen; braking reaction before FCW trigger	visual FCW is perceived
S82	52	H	1	No	-2,617	-1,316	partially	5 3 8 4 0	5 3 40	gaze come back to the road at FCW trigger	pedestrian is seen only at the end of the 2nd task	FCW is not perceived
S83	48	F	1	Yes	No fully release	No braking	undefined	5 3 8 4 0	5 3 8 4 0	do the 2nd task entirely; no confirmation from camera inside the car (record failure)	situation is understood thank to FCW	audio FCW is perceived
S84	46	H	1	No	-2,188	-1,821	partially	5 3 8 4 0	5 4 0 not seen	no effect of 2nd task as gaze stays on the road until braking is initiated, then gaze goes to the 2nd task screen	pedestrian setting up is seen; brakes before FCW trigger	visual FCW confirm the braking reaction
S85	47	H	1	No	-1,813	-1,36	N	5 3 8 4 0	I prefer looking the pedestrian instead of the 2nd task	glance back to the road during the 2nd task	brakes before or at FCW trigger; no effect of FCW	
S105	51	H	1	No	-2,133	-1,789	N	5 3 8 4 0	I see nothing	gaze stays on the road	pedestrian setting up is seen; brakes before FCW trigger	audio FCW is perceived, visual FCW no perceived
S107	40	H	1	Yes	-0,805	-0,578	Y	5 3 8 4 0	5 3 and something else	fully distracted until the 2nd task ends		audio FCW is not perceived, visual FCW is perceived at the end of the 2nd task
S108	41	F	1	No	-2,125	-1,75	N	5 3 8 4 0	8 4 0 4 I miss the first one	gaze stays on the road and the pedestrian until vehicle stops	pedestrian setting up is seen; brakes before FCW trigger	visual FCW is perceived at the end of 2nd task, audio FCW is not perceived consciously
S109	33	H	1	Yes	-0,543	No braking	Y	5 3 8 4 0	2 4 6 0 8	difficulty to understand instructions; fully distracted until FCW triggers		
S111	55	F	1	No	-2,301	-2	N	5 3 8 4 0	3 8 and I don't know	gaze stays on the road until braking is initiated	pedestrian setting up is seen; brakes before FCW trigger	FCW not perceived (not sure)
S112	26	H	1	No	-1,961	-1,641	undefined	5 3 8 4 0	8 4 0	eye tracker video can't confirm the effect of the 2nd task	pedestrian setting up is seen out of the corner of eyes	foggy perception of FCW
S114	40	F	1	No	-1,957	-1,531	partially	5 3 8 4 0	8 4 0 I miss the beginning	glance back to the road during the 2nd task	pedestrian is seen from the corner of the eyes after having seen "tâche visuelle", then glance back to the road; brakes at the same time of FCW trigger	visual FCW perceived, FCW can be non-useful or neutral
S115	24	F	1	No	-2,028	-1,664	partially	5 3 8 4 0	I see nothing	glance back to the road during the 2nd task	peripheral vision perceives movement => glance back to the road; brakes at same time of FCW trigger; FCW seems to be useful in this case; FCW may be responsible of the braking	audio and visual FCW is perceived

C-L scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S57	22	H	1	Yes	-0,461	No braking	Y	4 2 7 5 8	3 2 9 and 8 finally	do the 2nd task entirely	
S58	30	F	1	No	-2,672	-2,149	N	4 2 7 5 8	No answer	apparently no effect of the 2nd task; one digit seems to be seen "7"	expect something to happen during a 2nd task but not necessarily at this one
S59	51	F	1	No	<-4s	-1,058	partially	4 2 7 5 8	2 5 5 7	glance between 2nd task and the road	miss the first digits of the sequence
S60	22	F	1	No	-2,348	-1,996	N	4 2 7 5 8	I haven't see the beginning	gaze is located on the cyclist and goes to the 2nd task screen only after the braking	
S136	28	F	1	No	-2,59	-2,082	N	4 2 7 5 8	I see only the 8	gaze stays on the road until participant reacts; cyclist is seen on the right and also its setting up	participant expects a cyclist's fall
S137	28	H	1	No	-1,699	-1,406	partially	4 2 7 5 8	7 5 8	glance back to the road during the 2nd task	cyclist setting up is seen
S138	54	H	1	No	<-4s	-2,348	N	4 2 7 5 8	5 8 I miss all the first digits	gaze stays on the road until the vehicle stops	cyclist is seen on the pavement and also the setting up
S139	39	H	1	No	-2,375	-2	N	4 2 7 5 8	7 ,,,	gaze stays on the road until the vehicle stops	cyclist shifting is seen at the last moment; the cyclist is not seen initially on the pavement
S140	45	F	1	No	-2,32	-2,062	N	4 2 7 5 8	I see nothing	gaze stays on the road until the vehicle stops	the cyclist is not seen on the pavement but only when shifting on the road
S143	53	H	1	Yes	-1,195	-0,625	partially	4 2 7 5 8	4 2 5 8 and I don't know	steering manoeuver, impact with oncoming traffic but not with the cyclist	steering manoeuver first to avoid cyclist but without noticing oncoming traffic, during the manoeuver, participant notices the oncoming traffic

FCW 2s												
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S66	48	H	1	No	-2,543	-2,141	N	4 2 7 5 8	4 2 5 8 and I forget one digit	no effect of the 2nd task	look at the cyclist and keep looking at him until braking because anticipate; I brake before FCW trigger; FCW is found useful	FCW perceived
S67	38	H	1	No	-2,117	-1,477	Y	4 2 7 5 8	4 5 7 ... at the end	gaze is not on the road until brakes is triggered		visual FCW perceived more than audio
S68	46	F	1	No	-2,559	-2,176	N	4 2 7 5 8	2 7 8		cyclist is seen on the pavement and also the setting up; no memories of looking at the 2nd task	
S69	25	F	1	No	-2,054	-1,449	partially	4 2 7 5 8	No answer	eye tracker video shows that gaze leaves only once the road during the 2nd task	react after seeing the cyclist setting up; react at the same moment of FCW trigger	
S70	54	F	1	Yes	-1,309	-0,367	Y	4 2 7 5 8	No answer	focus on the 2nd task because few completion during the familiarization scenario	leave the 2nd task due to the FCW; visual FCW is useless as the cyclist is more visible than the message "freinez"	audio and visual FCW perceived
S71	37	H	1	No	-2,5	-1,808	N	4 2 7 5 8	4 2 7 5 8	speed reduction after the audio announce of the 2nd task; the 2nd task ends before the cyclist is setting up	cyclist is seen on the pavement; the cyclist setting up is also seen; FCW triggers is perceived as too late	FCW perceived
S72	51	H	1	No	<-4s	-2,035	partially	4 2 7 5 8	2 7 5 8	gaze come back to the road during the 2nd task;, after handling the situation the gaze goes back to the 2nd task screen	cyclist setting up is seen and the 1st digit (at least) of the 2nd task has been missed; FCW is not perceived as useful or annoying	FCW perceived
S73	45	F	1	No	-0,836	-0,453	Y	4 2 7 5 8	4 2 7 and I don't remember	fully distracted until FCW trigger	stops the 2nd task due to FCW audio alert	audio FCW perceived
S74	43	H	1	No	-2,547	-2,023	N	4 2 7 5 8	5 and 8 that's all	gaze is on the road and only goes to the 2nd task screen after having handle the situation	brake before FCW signal; FCW has no effect and does not help to confirm the emergency situation	FCW perceived
S127	46	F	2	No	-2,227	-1,731	partially	4 2 7 5 8	not see 2 7 8 and I have not see	gaze is on the cyclist when on position on the road but there are some glances when cyclist starts to shift	braking is due to the FCW signal; FCW is useful	audio FCW perceived
S128	52	H	2	No	-2,539	-2,273	N	4 2 7 5 8	1 2 7 heu 1 2 7 8	no effect of the 2nd task as participant brakes when the cyclist begins to steer on the road	cyclist setting up is seen; answer to the 2nd task are forgotten due to the emergency situation	no memories of FCW perception
S129	39	F	2	No	-1,934	-1,574	partially	4 2 7 5 8	I see a 5 7 heu a 8 rather, a 8 and 7	glance back to the road and potentially react after FCW	no memory if braking is before during or after FCW trigger; FCW is seem to have a contribution	audio FCW is perceived
S131	44	H	2	No	-1,57	-1,063	Y	4 2 7 5 8	4 2 5 7 8 I am not sure	fully distracted	FCW triggers the braking reaction; FCW is perceived as useful	audio FCW is perceived
S132	49	H	2	No	-3,274	-2,543	N	4 2 7 5 8	I see the last number 8 only	no effect of the 2nd task; gaze stays on the road until the vehicles sops	cyclist is seen on the pavement and also the setting up; brakes before the FCW; FCW is not useful as danger comes from the side	visual FCW is perceived, less audio
S133	37	H	2	No	-2,781	-2,356	N	4 2 7 5 8	1 2 5 8	cyclist setting up is seen; brakes before FCW;	FCW 1st triggers can be annoying; with habits the device will become nor useful nor useless	audio FCW perceived, visual not
S134	35	H	2	No	-1,227	-0,656	Y	4 2 7 5 8	4 2 7 then I hit someone	cyclist setting up is not seen	find FCW not useful	audio FCW perceived

FCW 1.7s													
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S86	50	F	1	No	-2,446	-1,781	N	4 2 7 5 8	I only see a 8	gaze stays on the cyclist until vehicle stops, then gaze goes on the 2nd task screen	no memories of seeing the cyclist setting up	FCW not perceived (no memories)
S87	54	F	1	Yes	-0,465	No braking	Y	4 2 7 5 8	No answer	glances back to the road during 2nd task; braking reaction after the impact	cyclist is seen before FCW trigger, braking trigger is done after seeing the cyclist close to the impact	FCW is not perceived
S88	55	H	1	No	-2,554	-2,25	N	4 2 7 5 8	I see the last one 8 because of the cyclist	gaze stays on the cyclist until vehicle stops, then gaze goes on the 2nd task screen	cyclist is seen on the pavement and gaze stays on the cyclist; the 1st and 2nd number of the task is seen but no response because forgotten	FCW not perceived at all
S89	35	F	1	No	-2,117	-1,801	partially	4 2 7 5 8	4 2 7 5	glance back to road during the 2nd task	more alert when a 2nd task is triggered	visual and audio FCW not perceived (not sure)
S90	55	H	1	No	-1,852	-1,481	partially	4 2 7 5 8	3 8 no more	gaze back to road at the end of cyclist setting up in position	look at the 2nd task until peripheral vision is attracted by the cyclist; FCW is disturbing as the attention was focused on the cyclist and FCW attracts the gaze; FCW allows to react by braking	audio and visual FCW perceived
S91	44	F	1	No	<-4s	-1,218	partially	4 2 7 5 8	I see only the 4 2 no more	gaze is located on the cyclist during the approach; glance on the 2nd task screen for the 2 first number	cyclist is seen on the pavement and during the setting up	no perception of FCW
S92	44	H	1	No	-2,546	-2,203	N	4 2 7 5 8	I see nothing I was focused on the cyclist	no effect of the 2nd task	give up on the 2nd task during the cyclist setting up; braking before the FCW triggers; FCW triggers too late and considered as useless	FCW perceived
S93	44	H	1	No	-2,586	-2,015	N	4 2 7 5 8	the last two 5 8	the first numbers of the 2nd task has been missed;		
S94	49	F	1	No	-1,234	-0,871	Y	4 2 7 5 8	4 2 5 7 8	fully distracted until FCW triggers	braking appears to be the best manoeuver to do	audio FCW seems perceived (not consciously), no perception of visual FCW
S95	52	H	1	No	<-4s	-1,347	partially	4 2 7 5 8	7 5 4 3 I don't know	gaze is back to the road just before the cyclist is on position on the road	cyclist setting up is seen; braking before FCW; FCW confirm the braking manoeuver	visual FCW perceived
S97	29	H	2	Yes	-1,617	-1,211	Y	4 2 7 5 8	it begins by a 4	fully distracted	FCW alerts to focus back on the road	audio FCW perceived
S100	46	F	2	No	-2	-1,726	partially	4 2 7 5 8	I have not seen the number I see 42 8 and	gaze is back on the road after the cyclist is on position on the road	cyclist is seen when approaching, the cyclist will cross car path	
S101	41	F	2	No	-2,421	-2,003	partially	4 2 7 5 8	see nothing	cyclist setting up is not seen	look at the screen then come back to the road because of something moving; brake at the same moment of FCW trigger; FCW is useful for safety distance	audio FCW not perceived, visual FCW perceived
S103	36	F	2	No	-2,359	-1,875	partially	4 2 7 5 8	7 5 7 8	alternative glance to the road and to the 2nd task	cyclist is seen on the pavement and the setting up; look both at the screen and the cyclist; brake at the same time FCW time triggers; FCW disturbs a little	audio and visual FCW perceived
S104	55	H	2	Yes	-0,637	-0,184	Y	4 2 7 5 8	not possible to repeat the digit	fully distracted until impact	2nd task is highly disturbing	audio FCW not perceived
S106	39	F	2	No	-2,907	-2,555	N	4 2 7 5 8	there was a 3 and a 8 at the end	gaze is located in front, gaze goes to the 2nd task after vehicle stops	cyclist setting up is seen	audio FCW is not perceived, visual FCW is perceived

Additional experiment

TL-CR scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S144	42	H	1	No	-0,699	-0,519	Y	72 54 48 56	72 54 42 I don't know	do the 2nd task	the cyclist is seen at the last moment (the cyclist appears suddenly)
S145	43	H	2	No	-2,981	-1,121	Y	72 54 48 56	72 I don't know I don't know I don't know	do the 2nd task	the C is seen during the turning manoeuver
S146	43	F	1	No	-0,539	-0,281	Y	72 54 48 56	56 I don't know .. I don't know	do the 2nd task	surprised by C appearance, the C is seen thank to peripheral vision
S148	25	H	2	No	>-3s	-0,719	Y	72 54 48 56	88 pass pass …	do the 2nd task	the C is seen at the last moment, between a visual control to the left and when gaze comes back in front
S149	27	F	1	Yes	-1,062	-0,781	Y	72 54 48 56	I don't know .. I don't know ..		choice to prioritize driving after having seen the C; the C is seen after having started to turn
S150	53	F	2	Yes	-1,879	-1,558	Y	72 54 48 56	pass pass pass pass		the C is seen during the turning manoeuver
S151	55	F	1	No	-0,543	-0,301	Y	72 54 48 56	72 42 i don't know 49	car only decelerates and don't stop	the C is seen engaged in the intersection, choice to prioritize driving
S152	29	F	2	Yes	-2,019	No braking	Y	72 54 48 56	72 I don't know 48 42	participant has not noticed the C at all => remove from analysis	the C is not seen at all
S153	42	F	1	Yes	-0,984	No braking	Y	72 54 48 56	72 48 I don't know 42	do the 2nd task	the C is seen at the impact
S154	28	H	2	Yes	-1,621	No braking	unknown	72 54 48 56	record failure	participant has not noticed the C at first (consider the vru as a pedestrian)	participant declares accelerating to avoid the C (not confirmed by the speed variation afterwards)
S159	25	F	1	No	>-3s	>-3s	Y	72 54 48 56	72 heu I don't kow I don't know		the C is seen at the beginning of the turning manoeuver
S160	25	H	2	No	>-3s	>-3s	Y	72 54 48 56	72 pass 48 pass	do the 2nd task; apply brakes far before the intersection	progressive braking (no emergency braking)
S168	45	F	2	No	-2,601	-1,703	Y	72 54 48 56	72 54	do the 2nd task	the C is seen late after being in the intersection
S169	47	H	1	No	>-3s	-0,922	Y	72 54 48 56	81 56 .. I don't know	do the 2nd task	progressive braking
S172	25	F	2	Yes	-0,902	-0,664	Y	72 54 48 56	72 .. 72 42	do the 2nd task	the C seems to have been seen far away before the intersection but is analyzed during the turning manoeuver
S174	27	H	1	Yes	-1,321	-0,922	Y	72 54 48 56	72 54 .. pass	do the 2nd task	the C is seen at the entering in the intersection
S179	26	H	1	No	>-3s	-0,3	Y	72 54 48 56	81 I don"t know	do the 2nd task; this is 2nd braking trigger, when approaching the intersection a 1st braking is applied continuously before the C is triggered	situation is less urgent as the C is already engaged in the intersection
S180	39	H	2	Yes	-0,594	-0,32	Y	72 54 48 56	72 54 48 ..	do the 2nd task	the C is seen late, very close to the car

FCW 2s												
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S155	28	H	1	Yes	-0,84	-0,621	Y	72 54 48 56	(mumble) I don't know I don't know		the C is seen thank to audio FCW	audio FCW perceived, visual FCW not perceived
S156	26	F	2	No	-2,196	-0,946	Y	72 54 48 56	I don't know	No emergency situation (see the scenario video)		audio FCW is perceived => participant is in alert, after the beep automatic braking reaction
S157	46	H	1	No	-0,898	-0,562	Y	72 54 48 56	64 42	do the 2nd task until FCW triggers	the C is seen at the last moment	audio and visual FCW is perceived after having reacted, FCW confirm the presence of the C but scared and surprised => brake too much
S158	33	H	2	No	>-3s	>-3s	Y	72 54 48 56	72 (mumble)	No emergency situation (see the scenario video)		audio and visual FCW is perceived; FCW can be useful if lack of vigilance; here FCW is stressful because can be trigger at any moment
S161	26	H	1	Yes	-1,328	No braking	Y	72 54 48 56	72 48 I don't know ..	do the 2nd task until FCW triggers	I hit a motorcycle	visual FCW is perceived; FCW has no benefits as triggered too late
S162	27	F	2	Yes	-0,68	-0,32	Y	72 54 48 56	I don't know 54 48	do the 2nd task until FCW triggers	the C is seen at the impact	audio and visual FCW perceived, has understood audio signal meaning; FCW is not responsible of the braking reaction
S163	28	F	1	Yes	-0,882	-0,562	Y	72 54 48 56	heu (mumble)	do the 2nd task		audio and visual FCW perceived; FCW is useless as it triggers too late, the situation is well-understood and react before its trigger
S164	28	F	2	No	>-3s	-0,75	Y	72 54 48 56	54 I don't know 48 I don't know	do the 2nd task		no memories of FCW trigger
S165	36	H	1	No	>-3s	>-3s	Y	72 54 48 56	72 40 it goes too fast	do the 2nd task until FCW triggers	NO EMERGENCY SITUATION (important speed variation)	audio and visual FCW is perceived, participant thinks that the FCW trigger for the bus
S166	35	H	2	No	>-3s	-1,265	Y	72 54 48 56	72 54 I don't know I don't know	do the 2nd task until FCW triggers	participant remembers the scenario as a crossing pedestrian	FCW audio not perceived, visual FCW is seen after having react; no effect of FCW
S167	54	H	2	No	-1,078	-0,738	Y	72 54 48 56	72 54 48 I don't know	do the 2nd task	no memories of the scenario	audio and visual FCW not perceived
S171	38	H	1	No	NA	NA	Y	72 54 48 56	72 54	do the 2nd task until FCW triggers, too important speed variation between C trigger and C appearance + lag during record		visual FCW is perceived after car stopped, audio FCW is not perceived, participant doesn't know if should follow FCW message and if it is linked to the C
S173	37	F	1	Yes	-2,898	-1,718	Y	72 54 48 56	72 54 48 ..	do the 2nd task until FCW triggers	brake before FCW, FCW signal makes ma panic but confirm the choice to brake	visual FCW perceived, audio not perceived
S175	30	H	1	No	NA	NA	Y	72 54 48 56	72 I don't know .. I don't know	Do the 2nd task until FCW triggers; too important speed variation between C trigger and C appearance => NO EMERGENCY SITUATION		audio and visual FCW perceived, no benefits from FCW
S176	32	H	2	Yes	-0,539	-0,238	Y	72 54 48 56	I don't know I don't know.. ..	Do the 2nd task until FCW triggers	brake before FCW, FCW signal is analyzed after handling the situation	audio FCW not perceived, visual not sure to perceive it, FCW is seen after car stops
S177	55	H	2	Yes	-1,297	-1,02	Y	72 54 48 56	72 56 48 ..	Do the 2nd task until FCW triggers		

TL-PL scenario

Without FCW											
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment
S144	42	H	2	No	-3,691	-3,133	record failure	48 42 56 48	record failure	the participant is doing the 2nd task but record failure during the scenario	the pedestrian is seen at the beginning of the crossing
S145	43	H	1	No	-3,136	-2,679	Y	48 42 56 48	36 I don't know, I don't know I don't know	do the 2nd task	the P is seen between the pavement and the road
S146	43	F	2	No	-3,617	-3,164	Y	48 42 56 48	48 I don't know 42 ..	do the 2nd task	the P is seen on the pavement, focus on the crossing P even if try to do the 2nd task simultaneously
S148	25	H	1	Yes	-0,996	No braking	Y	48 42 56 48	pass pass	do the 2nd task	2nd task disturbs, multi-task is stressful (visual control + turning + calculus)
S149	27	F	2	No	-3,039	-2,64	Y	48 42 56 48	I don't know 42 I don't know	do the 2nd task	the 2nd task is done in background
S150	53	F	1	No	-3,363	-2,703	Y	48 42 56 48	pass pass .. pass	try to do the 2nd task	the calculus is too complex => pass, the P is on the opposite way
S151	55	F	2	No	-1,32	-1,063	unknown	48 42 56 48	record failure		the P is seen at the beginning of his crossing; progressive braking
S152	29	F	1	No	-3,32	-1,863	Y	48 42 56 48	45 I don't know I don't know I don't know	do the 2nd task	the P is seen, focus on driving and the crossing P
S153	42	F	2	No	-1,918	-1,648	Y	48 42 56 48	48 42 48 ..	do the 2nd task	the crossing P is seen on the pavement, progressive braking to let the P cross
S154	28	H	1	Yes	-2,16	-1,949	Y	48 42 56 48	I don't know I don't know I don't know	participant is surprised by the P crossing	focus on the road because of the emergency situation, emergency braking to let the P cross
S159	25	F	2	No	-3,445	-1,715	Y	48 42 56 48	48 49 I don't know I don't know	do the 2nd task	the P is seen during the crossing (at the beginning or in the middle of the opposite lane), the 2nd task is not disturbing
S160	25	H	1	No	-2,293	-1,895	Y	48 42 56 48	(mumble) 56 64 pass	do the 2nd task	the P is seen on the pavement and also the crossing, progressive braking (no emergency braking)
S168	45	F	1	No	-3,379	-2,661	Y	48 42 56 48	48 .. 54 ..	do the 2nd task	the P is seen on the pavement and also the crossing
S169	47	H	2	No	-3	-2,5	Y	48 42 56 48	48 42 .. 48	do the 2nd task	
S172	25	F	1	No	<-4s	-2,761	Y	48 42 56 48	48 42 pass	do the 2nd task	the P is seen during the crossing, progressive braking (no emergency manoeuver)
S174	27	H	2	No	-3,04	-2,602	Y	48 42 56 48	48 42 56 42	do the 2nd task	low car speed in case a P would cross and the P is seen of the pavement on the left, moderate braking (no emergency manoeuver)
S179	26	H	2	No	-1,098	-0,668	Y	48 42 56 48	42 42 .. 36	do the 2nd task	progressive braking (no emergency braking), more alert on the surrounding environment, the 2nd task need les resources due to habit
S180	39	H	1	No	-3,305	-2,664	Y	48 42 56 48	48 42 .. 48	do the 2nd task	the P is seen but no memories of where, progressive braking as the P is seen crossing

FCW 2s												
Subject n°	Age	Gender	1st or 2nd scenario experimented	Accident (Y/N)	Gas release time	Brake trigger time	Do the 2nd task (Y/N/partially)	2nd task correct answer	Participant's answer	Comment / remark	Participant's comment	React to FCW
S155	28	H	2	No	-1,43	-1,114	partially	48 42 56 48	heu	try to do the 2nd task	the P is seen at the beginning of the crossing, focus on the road when the P was crossing, progressive deceleration to let P cross (no emergency braking)	audio FCW perceived and not the visual one, FCW not annoying
S156	26	F	1	No	-2,582	-2,184	N	48 42 56 48	I don't know	participant forgets to answer during the critical situation (answers are given for the others digits series)	the P is seen crossing, braking trigger at the same time of FCW trigger	FCW confirms the reaction (not sure if the braking has initiated the braking)
S157	46	H	2	No	<-4s	-2,39	Y	48 42 56 48	64 42	do the 2nd task until FCW triggers	the P is seen on the pavement, progressive braking (no emergency braking)	audio and visual FCW perceived, annoying signal as the situation was well-understood and handled => don't understand the trigger reason
S158	33	H	1	No	-3,008	-1,848	Y	48 42 56 48	48	do the 2nd task	the P is seen on the road, the situation is well-understood	audio FCW perceived, visual FCW not perceived, FCW accentuates the emergency braking
S161	26	H	2	No	-2,606	-2,125	Y	48 42 56 48	I don't know 42	do the 2nd task until FCW triggers	the P is seen at the beginning of the crossing, slowly decelerate (no emergency braking)	only visual FCW is perceived, it helps confirm the choice to stop
S162	27	F	1	Yes	-1,09	-0,879	Y	48 42 56 48	48 I don't know	do the 2nd task until FCW triggers	P is seen at the last moment (hidden by the A-pillar of the vehicle), still adapting to the simulator environment, braking is not triggered by FCW	audio FCW is perceived first then visual, search the meaning of the audio signal which is not understood when it triggers but is understood after handling the situation
S163	28	F	2	Yes	-3,539	-1,39	Y	48 42 56 48	45 (mumble)	do the 2nd task until FCW triggers	difficulty to handle turning manoeuver	audio FCW perceived first then visual, audio FCW gives an information
S164	28	F	1	No	-3,016	No braking	Y	48 42 56 48	48 42 I don't know ..	do the 2nd task until FCW triggers, no accident as the car accelerates and passes the impact location before P arrives	difficulty to handle turning manoeuver	FCW audio perceived first then visual
S165	36	H	2	No	-2,059	-1,738	Y	48 42 56 48	48 36 I don't know	do the 2nd task until FCW triggers	the P is seen on the pavement and anticipates P crossing due to his orientation, progressive braking (no emergency manoeuver)	visual FCW more perceived than audio, no benefits of FCW as the situation is well understood and react before FCW trigger
S166	35	H	1	No	<-4s	-0,61	Y	48 42 56 48	36 42	do the 2nd task until FCW triggers	the P is seen crossing in the middle of the opposite lane	audio FCW perceived and make me brake, visual FCW not perceived
S167	54	H	1	No	-3,808	-1,75	Y	48 42 56 48	48 42 heu	do the 2nd task until FCW triggers	the P (hidden by a LV) is seen during the crossing, brake before or at the same moment of FCW trigger	audio FCW not perceived, visual FCW perceived and enhanced emergency braking
S171	38	H	2	No	-2,547	-2,125	Y	48 42 56 48	48 56 49 42	do the 2nd task entirely	slow down because expect a crossing P from the right and then see a P crossing from the left, progressive braking (no emergency manoeuver)	FCW audio and visual not perceived
S173	37	F	2	Yes	-0,984	No braking	Y	48 42 56 48	48 42	do the 2nd task until FCW triggers	the P is seen at the moment of the impact,	FCW audio and visual perceived simultaneously, FCW makes me panic
S175	30	H	2	No	-2,058	-1,843	Y	48 42 56 48	I don't know 42 .. 26	do the 2nd task entirely, participant's mistake for crossing direction of the P	P is seen during the crossing from the right to the left	visual FCW perceived, audio FCW not perceived, no benefit of FCW or no annoyance
S176	32	H	1	No	-2,824	-2,082	Y	48 42 56 48	I don't know I don't know	do the 2nd task until FCW triggers	I brake before FCW triggers, the P is seen during the crossing	audio perceived first then visual, stressful signal because I react before FCW
S177	55	H	1	No	-1,285	-0,91	Y	48 42 56 48	48 42	do the 2nd task until FCW triggers	the word "brake" accentuates the braking	visual FCW perceived after braking, not sure to perceive audio FCW

E. Parametric simulation table per scenario

All Pedestrian cases (P-All)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	59	37	13	65	55	34	68	62	54	71	65	61	63	41	16	69	60	39	72	67	59	75	70	66	63	41	16	69	60	39	72	67	60	75	70	66
Mitigated (%)	14	24	35	11	11	23	10	8	9	9	7	6	14	24	37	11	11	23	10	7	8	9	7	6	14	24	37	11	11	23	10	7	8	9	7	6
No effect (%)	27	39	52	24	34	43	22	30	37	20	28	33	23	35	47	20	29	38	18	26	33	16	23	28	23	35	47	20	29	38	18	26	32	16	23	28

Pedestrian Crossing Nearside (P-CN)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	55	33	7	60	50	30	64	56	49	69	61	56	58	35	9	63	53	32	67	60	52	71	64	59	58	36	9	63	54	33	67	60	53	72	64	59
Mitigated (%)	19	25	37	17	13	23	16	10	10	14	9	8	20	26	38	18	13	24	17	10	10	15	9	8	20	26	38	18	13	24	17	10	10	15	10	8
No effet (%)	26	42	56	23	37	47	20	34	41	17	30	36	22	39	53	19	34	44	17	30	38	14	27	33	22	38	53	19	33	43	16	30	37	13	26	33

Pedestrian Crossing Farside (P-CF)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	72	39	9	82	69	36	85	81	69	87	84	79	75	42	12	86	72	40	89	85	73	90	87	83	75	42	12	86	72	40	89	85	73	90	87	83
Mitigated (%)	13	34	47	6	12	33	6	5	10	5	5	4	13	34	48	6	12	33	6	5	10	5	5	4	13	34	48	6	12	33	6	5	9	5	5	4
No effet (%)	15	27	44	12	19	31	9	14	21	8	11	17	12	24	40	8	16	27	5	10	17	5	8	13	12	24	40	8	16	27	5	10	18	5	8	13

Pedestrian Longitudinal (P-L)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	74	53	21	84	69	47	90	79	74	90	79	79	74	53	21	84	69	47	74	79	74	90	79	79	74	53	21	84	69	47	90	79	74	90	79	79
Mitigated (%)	21	42	63	11	26	47	5	16	21	5	16	16	21	42	63	11	26	47	21	16	21	5	16	16	21	42	63	11	26	47	5	16	21	5	16	16
No effet (%)	5	5	16	5	5	6	5	5	5	5	5	5	5	5	16	5	5	6	5	5	5	5	5	5	5	5	16	5	5	6	5	5	5	5	5	5

Pedestrian Turning Left (P-TL)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	77	70	52	78	72	66	78	72	67	81	74	69	92	87	64	92	90	86	92	90	88	93	90	88	93	89	66	93	91	89	94	92	92	95	92	92
Mitigated (%)	5	7	13	5	7	5	5	7	4	4	6	4	1	3	18	1	2	2	1	2	2	1	2	2	0	3	18	0	2	1	0	2	0	0	2	0
No effet (%)	18	23	35	17	21	29	17	21	29	15	20	27	7	10	18	7	8	12	7	8	10	6	8	10	7	8	16	7	7	10	6	6	8	5	6	8

Pedestrian Turning Right (P-TR)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	75	70	51	75	70	68	75	70	68	77	72	70	91	88	62	91	89	87	91	89	87	91	91	89	92	89	62	92	89	87	92	89	87	92	91	89
Mitigated (%)	6	7	19	6	7	4	6	7	4	6	7	4	2	4	27	2	4	4	2	4	4	2	2	2	2	4	27	2	4	4	2	4	4	2	2	2
No effet (%)	19	23	30	19	23	28	19	23	28	17	21	26	7	8	11	7	7	9	7	8	9	7	7	9	6	7	11	6	7	9	6	7	9	6	7	9

All Cyclist cases (C-All)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	39	28	13	42	36	27	44	40	36	45	41	38	64	52	31	68	61	49	69	64	57	71	66	61	72	60	38	75	69	57	77	72	66	78	74	69
Mitigated (%)	8	11	20	6	6	10	6	5	5	6	5	3	7	12	25	5	6	12	4	5	6	4	5	5	6	11	26	4	6	12	4	4	6	4	4	5
No effect (%)	53	61	67	52	58	63	50	55	59	49	54	59	29	36	44	27	33	39	27	31	37	25	29	34	22	29	36	21	25	31	19	24	28	18	22	26

Cyclist Crossing Nearside (C-CN)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	37	24	11	41	33	23	43	36	31	44	38	34	66	51	32	69	60	47	71	63	55	72	65	58	75	62	42	78	71	58	80	74	66	81	76	69
Mitigated (%)	11	14	19	9	9	12	8	7	7	8	7	5	11	15	24	9	10	15	8	8	9	8	7	8	10	15	25	8	9	15	7	7	9	7	6	7
No effect (%)	52	62	70	50	58	65	49	57	62	48	55	61	23	34	44	22	30	38	21	29	36	20	28	34	15	23	33	14	20	27	13	19	25	12	18	24

Cyclist Crossing Farside (C-CF)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	47	30	10	52	45	30	53	50	44	54	51	48	76	57	30	81	74	54	83	77	70	84	80	74	86	67	40	90	83	65	92	87	81	93	89	85
Mitigated (%)	7	15	27	5	6	15	5	4	5	5	4	3	6	17	33	3	6	18	3	5	6	2	4	4	4	17	34	2	6	17	2	4	5	1	4	4
No effect (%)	46	54	63	43	49	55	42	46	51	41	45	49	18	26	37	16	20	28	14	18	24	14	16	22	10	16	26	8	11	18	6	9	14	6	7	11

Cyclist Longitudinal (C-L)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	61	46	12	69	62	48	74	72	66	77	74	72	68	50	14	74	67	49	76	74	68	81	77	75	68	51	14	75	67	50	77	75	69	81	77	75
Mitigated (%)	6	17	46	2	6	16	3	2	5	3	4	2	7	21	52	3	8	20	5	3	6	2	4	2	7	21	53	3	8	20	4	3	6	2	4	2
No effet (%)	33	37	42	29	32	36	23	26	29	20	22	26	25	29	34	23	25	31	19	23	26	17	19	23	25	28	33	22	25	30	19	22	25	17	19	23

Cyclist Turning Left (C-TL)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	60	51	28	62	57	47	64	60	54	65	61	57	76	68	39	78	73	63	80	76	70	80	77	73	81	73	42	82	79	69	85	82	77	87	84	80
Mitigated (%)	5	7	24	4	4	9	4	3	5	4	4	4	4	6	28	4	3	9	4	3	5	4	3	4	4	6	30	4	3	8	3	2	4	3	2	3
No effet (%)	35	42	48	34	39	44	32	37	41	31	35	39	20	26	33	18	24	28	16	21	25	16	20	23	15	21	28	14	18	23	12	16	19	10	14	17

Cyclist Turning Right (C-TR)

FOV (°)	30												50												70											
FCW (s)	1.7			2			2.3			2.6			1.7			2			2.3			2.6			1.7			2			2.3			2.6		
DR (s)	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2	0.6	0.9	1.2
Avoided (%)	29	24	13	30	27	23	32	29	27	33	30	28	63	56	37	64	60	52	67	63	57	69	64	59	71	64	44	73	69	61	75	71	65	76	72	68
Mitigated (%)	8	5	11	8	4	3	8	4	2	8	4	2	3	5	19	3	4	7	3	3	6	3	4	5	4	5	21	3	3	6	3	3	5	3	3	4
No effet (%)	63	71	76	62	69	74	60	67	71	59	66	70	34	39	44	33	36	41	30	34	37	28	32	36	25	31	35	24	28	33	22	26	30	21	25	28