Supporting the driver in conserving energy and reducing emissions

ecoDriver

D43.1: Eco-driving in the real-world: behavioural, environmental and safety impacts

(Version 18; 2016-08-10)

Subproject	SP4: Evaluation of Effectiveness
Work package	WP43: Behaviour, side effects and energy use
Task	T43.1, T43.2, T43.3

Authors	Guillaume Saint Pierre, Rino Brouwer, Jeroen Hogema, Ouren Kuiper, Philipp Seewald, Pablo Mejuto, Eva García, Antonella Toffetti, Laura Borgarello, Paolo Capano, Olivier Orfila, Katja Kircher, Christer Ahlström, Mario Aleksic, Michael Henzler, Daryl Hibberd, Samantha Jamson, Frank Lai, Jan Loewenau, Jasper Pauwelussen and Oliver Carsten
Dissemination level	Public (PU)
Status	Pre-final
Due date	01/03/2016
File Name	D43.1 Eco-driving in the real world_resubmitted August 2016.docx

IP Coordinator	Oliver Carsten, University of Leeds
	The research leading to these results has received funding from the European Union Seventh Framework Programme under grant agreement n° 288611. FP7-ICT-2011-7: Information and Communication Technologies Low carbon multi-modal mobility and freight transport

Abstract	This deliverable describes the results of analyses of the real world trials of the project eco-driving assistance systems. Several different systems with different characteristics and features were tested. Due to confidentiality constraints we could compare with a baseline two systems developed within the project: the Full ecoDriver System and the ecoDriver App. The other systems developed were combined for different comparisons. As a global picture of the ecoDriver results, the embedded systems (all the developed systems except the ecoDriver App and the TomTom system), provided more benefits than the ecoDriver App. The embedded systems performed better because of their integration into the vehicle and their ability to exploit vehicle data to create advice. On the other hand, the non-embedded systems such as the ecoDriver App relied on internal computation mainly based on GPS information, which makes them considerably cheaper. It is therefore not surprising to observe this difference. Adding a haptic pedal produces small additional benefits compared to only providing visual information. The smaller impact of the ecoDriver App in the controlled drives is counterbalanced by some positive results during the naturalistic experiments, especially in saving energy.

IP Coordinator	Oliver Carsten, University of Leeds
SEVENTH FRAMEWORK PROGRAMME	The research leading to these results has received funding from the European Union Seventh Framework Programme under grant agreement n° 288611. FP7-ICT-2011-7: Information and Communication Technologies Low carbon multi-modal mobility and freight transport

Control sheet

Version history			
Version	**Date**	**Main author**	**Summary of changes**
1	19/01/2016	Guillaume Saint Pierre	All contributions plus additional formatting
2	01/02/2016	Guillaume Saint Pierre	Additional material
3	10/02/2016	Jeroen Hogema	Updating analysis tables
4	11/02/2016	Samantha Jamson	Layout and template
5	13/02/2016	Guillaume Saint Pierre	Additional material
6	18/02/2016	Guillaume Saint Pierre	Additional material
7	23/02/2016	Guillaume Saint Pierre	Additional material
8	25/02/2016	Eva Garcia	Additional CTAG material
9	25/02/2016	Samantha Jamson	Changes made based on reviewer's comments
10	26/02/2016	Samantha Jamson	Changes to summaries
11, 12	28/02/2016	Guillaume Saint Pierre	Updating tables and figures
13	29/02/2016	Rino Brouwer	several changes to text, structure
14	29/02/2016	Guillaume Saint Pierre	Integration of last contributions, update of tables
15	01/03/2016	Oliver Carsten	Editorial updates
16	01/03/2016	Samantha Jamson	Editorial updates
17	20/06/2016	Daryl Hibberd	Addition of results of Leeds trial
18	09/08/2016	Oliver Carsten	Further edits

	Name
Prepared by	Guillaume Saint Pierre
Reviewed by	Magnus Hjälmdahl, Samantha Jamson, Oliver Carsten
Authorised by	Guillaume Saint Pierre
Verified by	Oliver Carsten

Circulation	
Recipient	**Date of submission**
Project partners	04/03/2016
European Commission	04/03/2016

Table of contents

1 Introduction 1

2 Executive summary 4

2.1 Overview of the systems and experimental designs 4
2.2 Hypotheses and analysis methods 8
2.3 Overview of results 14
2.4 Main findings — energy and emissions 18
2.5 Main findings — driver workload and attention 19
2.6 Main findings — driver speed 19
2.7 Main findings — time headway 20
2.8 Main findings — driver behaviour in events 21
2.9 Main findings — the four golden rules 21
2.10 Main findings — acceleration and deceleration 21
2.11 Overall conclusions 22
  2.11.1 Energy and emissions 22
  2.11.2 Safety (speed, time headway, accelerations) 23
  2.11.3 Golden rules of eco-driving 24
2.12 Lessons learned from the on-road trials in the ecoDriver project 25

3 Description of systems and their behaviour 26

3.1 CRF system 26
3.2 Daimler system 27
3.3 TomTom system 29
3.4 Leeds – TomTom system 30
3.5 BMW system 30
3.6 Full ecoDriver System (FeDS; CTAG, TNO, IKA, VTI and Leeds) 32
3.7 ecoDriver App (IFSTTAR, CTAG) 33
3.8 Event-based system behaviour 35

4 Definitions 37

4.1 Performance Indicators 37
4.2 Measures 37
  4.2.1 Direct (raw) measures 38
  4.2.2 Derived (pre-processed) measures 38
  4.2.3 Self-reported measures 38
  4.2.4 External measures 39
4.3 Descriptive variables 39
  4.3.1 Situational variables 40
  4.3.2 Events 40
4.4 Summary list of Performance Indicators 42

5 Analysis methods 46

5.1 Hypotheses tested 46

5.2 Hypotheses analysis methodology 48
    5.2.1 Step 1: Data pre-processing and data access 49
    5.2.2 Step 2: Select data 50
    5.2.3 Step 3: Identifying homogeneous situations 50
    5.2.4 Step 4: Data reduction 52
    5.2.5 Step 5: PI computation 54
    5.2.6 Step 6: Statistical analysis 54
    5.2.7 Practical considerations for data preparation 55
    5.2.8 Cumulative distribution vs. model results 56
5.3 Statistical comparisons and associated datasets 58
    5.3.1 Statistical comparisons 58
    5.3.2 Data cleaning 60
    5.3.3 Datasets contents 61

6 Results for energy and emissions 66
6.1 Hypothesis 1: Using an ecoDriver system will reduce the average fuel consumption and CO_2 emissions 66
6.2 Hypothesis 2: Using an ecoDriver system will reduce the average energy consumption 67
6.3 Hypothesis 3: Using an ecoDriver system will reduce the average NOx emissions 67
6.4 Summary 68
    6.4.1 Results combining all systems 69
    6.4.2 Results across road types 69
    6.4.3 Results across system categories 69

7 Results for driver workload and attention 70
7.1 Hypotheses 4 and 5: Using an ecoDriver system will increase driver workload 70
7.2 Hypotheses 6, 7 and 8: Using an ecoDriver system will decrease driver attention 71
7.3 Summary 74

8 Results for driver behaviour 75
8.1 Introduction 75
8.2 Hypothesis 9: Using an ecoDriver system the average velocity when cruising will be lower . 75
8.3 Hypothesis 10: Using an ecoDriver system the average free velocity will be lower 76
8.4 Hypothesis 11: Using an ecoDriver system, the speed will change before intersections without traffic lights 76
8.5 Hypothesis 12: Using an ecoDriver system, the speed will change before zebra crossings ... 77
8.6 Hypothesis 13: Using an ecoDriver system, the speed will change before speedbumps 78
8.7 Hypothesis 14: Using an ecoDriver system, the speed will change before sharp curves 78
8.8 Hypothesis 15: Using an ecoDriver system, the speed will change at crests 79
8.9 Hypothesis 16: Using an ecoDriver system, the speed will change before speed limit changes 80
8.10 Hypothesis 17: Using an ecoDriver system, the time headway distribution to leading vehicle will change 80
8.11 Hypothesis 18: Using an ecoDriver system, there will be shorter distances to vehicles before intersections without traffic light 81

8.12 Hypothesis 19: Using an ecoDriver system, there will be shorter distances to vehicles before zebra crossings 82
8.13 Hypothesis 20: Using an ecoDriver system, there will be shorter distances to vehicles before speedbumps 82
8.14 Hypothesis 21: Using an ecoDriver system, there will be shorter distances to vehicles before sharp curves 83
8.15 Hypothesis 22: Using an ecoDriver system, there will be shorter distances to vehicles at crest 83
8.16 Hypothesis 23: Using an ecoDriver system, there will be shorter distances to vehicles before speed limit changes 84
8.17 Hypothesis 24: Using an ecoDriver system, there will be more red or amber light violations 84
8.18 Hypothesis 25: Using an ecoDriver system, there will be fewer overtakings 84
8.19 Hypothesis 26: Using an ecoDriver system, there will be less overspeeding 85
8.20 Hypothesis 27: Using an ecoDriver system, the average rpm when shifting up will be reduced 85
8.21 Hypothesis 28: Using an ecoDriver system, the weighted average engine rpm will be decreased 86
8.22 Hypothesis 29: Using an ecoDriver system, the variability of speed profiles will be decreased 87
8.23 Hypothesis 30: Using an ecoDriver system, the use of the engine brake will be improved ... 88
8.24 Hypothesis 31: Using an ecoDriver system, the acceleration distribution will change 89
8.25 Hypothesis 32: Using an ecoDriver system, the deceleration distribution will change 89
8.26 Hypothesis 33: Using an ecoDriver system, acceleration after being stationary will be less aggressive 90
8.27 Hypothesis 34: Using an ecoDriver system, the acceleration distribution will change before intersections 90
8.28 Hypothesis 35: Using an ecoDriver system, the acceleration distribution will change before zebra crossings 91
8.29 Hypothesis 36: Using an ecoDriver system, the acceleration distribution will change before speed bumps 92
8.30 Hypothesis 37: Using an ecoDriver system, the acceleration distribution will change before sharp curves 93
8.31 Hypothesis 38: Using an ecoDriver system, the acceleration distribution will change at crests 94
8.32 Hypothesis 39: Using an ecoDriver system, the acceleration distribution will change before speed limit changes 95
8.33 Summary of results — driver speed 96
    8.33.1 Results combining all systems 97
    8.33.2 Results across road types 97
    8.33.3 Results across system categories 97
8.34 Summary of results — time headway 98
    8.34.1 Results combining all systems 99
    8.34.2 Results across road types 99

8.34.3 Results across system categories 99
8.35 Summary of results — driver behaviour in events 100
8.36 Summary of results — the four golden rules 100
8.36.1 Results combining all systems 101
8.36.2 Results across road types 101
8.36.3 Results across system categories 101
8.37 Summary of results — acceleration and deceleration 102
8.37.1 Results combining all systems 103
8.37.2 Results across road types 103
8.37.3 Results across system categories 103

9 Conclusions and discussion 104
9.1 Energy and emissions 104
9.2 Safety (speed, time headway, accelerations) 104
9.3 Golden rules 106
9.4 Main findings 106

10 Implications and lessons learned 108
10.1 Implications 108
10.2 Lessons learned 108

References 112

Index of figures

Figure 1: Countries where the trials took place 2
Figure 2: Overview of the data treatment and analysis process for a classical research hypothesis. ... 12
Figure 3: Overview of comparison types A through E 13
Figure 4: CRF prototypes 26
Figure 5: Coasting advice (right circle) shows the coasting advice icon (pedal and foot) and the reason for the advice: left turn at intersection in 133 m. 28
Figure 6: The distance to the lead vehicle can be shown in the right circle of the display. In the example shown, the lead vehicle is in the green zone, showing a safe distance. If the distance gets too low, coasting advice is shown. 28
Figure 7: Upcoming road signs and their distances are shown on the upper part of the display. The signs depicted here are not necessarily a reason to reduce speed so they are just shown to inform the driver. 29
Figure 8: Coasting advice (TomTom) 30
Figure 9: Gear shift advice (TomTom) 30
Figure 10: Green speed advice in speed bubble 30
Figure 11: Example of harsh cornering alert 30
Figure 12: Fuel consumption indications 30
Figure 13: Idling alert 30
Figure 14: The BMW dashboard showing the white dashboard and HUD background colour (right; reflecting average eco-driving performance) 31
Figure 15: The blue dashboard and HUD background colour (right; reflecting good eco-driving performance) 31
Figure 16: The red dashboard and HUD background colour (right; reflecting poor eco-driving performance) 31
Figure 17: The coasting icon in the dashboard left of the speedometer 32
Figure 18: Coasting advice provided in the HuD (here for a lower speed limit) 32
Figure 19: Main screen of FeDS 33
Figure 20: Advice to slow down for a curve (left) and the feedback on performance with a perfect score (right). 33
Figure 21: The main screen of the ecoDriver App with the performance tree (left) or with a map (right). 34
Figure 22: Feedback on harsh acceleration (left) and deceleration (right) 34
Figure 23: Feedback on gear shift performance 35
Figure 24: Example of advice to decelerate and the reason for deceleration (in this example a sharp curve) 35
Figure 25: Link between situational variables and events, extracted from a Fot-Net Data presentation from A. Zlocki and S. Koskinen (2016). 41
Figure 26: Overview of the data treatment and analysis process for a classical research hypothesis .. 49
Figure 27: Illustration of 6 different trips, sorted by time, available for data treatment and extraction. 50

Figure 28: Illustration for the data selection step. ... 50
Figure 29: Illustration of the simplest form of homogenisation process. ... 51
Figure 30: Illustration of the homogenisation process for multiple variables: combining “baseline/experiment” with “daylight”. ... 52
Figure 31: Illustration of the homogenisation process for multiple variables: combining variable “baseline/experiment” with "daylight" and "road type" ... 52
Figure 32: Illustration of the time-based subdivision of data. ... 53
Figure 33: Illustration of the PI computation step. The different sizes of the numbers represent their respective weights in the final data set. ... 54
Figure 34: Empirical cumulative density function of percentil_neg_acc_5 for experimental phase and baseline. ... 55
Figure 35: Empirical cumulative density function of the transformed sqrt_percentil_neg_acc_5 for experimental phase and baseline. ... 56
Figure 36: Empirical cumulative density function of the transformed sqrt_percentil_neg_acc_5 for the non-haptic and haptic systems before sharp curves on urban roads. ... 57
Figure 37: Overview of comparison types A through E. ... 58
Figure 38: Kms analysed by road type, experimental phase and system categories ... 65
Figure 39: Total NASA-TLX Workload Score (max. 60) ... 71
Figure 40. Percentage of glances to different targets per trip per road type. ... 72
Figure 41. Percentage of time looking at FeDS per road Type As a function of time. The vertical lines corresponds to the advice/feedback popup (t = 0 seconds) and when the popup disappears (t = 6 seconds). ... 73

Index of tables

Table 1: The systems tested within the ecoDriver project ... 5
Table 2: Overview of the experimental design at the different test sites ... 7
Table 3: ecoDriver "golden rules" of eco-driving and their respective performance indicator's (PI). ... 9
Table 4: Summary of the hypotheses studied in this deliverable ... 9
Table 5: Summary of results for all the hypotheses tested using a PI based approach. Significant cells are coloured from red (negative impact) to green (positive impact). ... 14
Table 6: System activity at events ... 36
Table 7: Overview of descriptive variables ... 39
Table 8: Summary list of PI used for the ecoDriver analyses ... 42
Table 9: Additional PIs considered in the analysis ... 45
Table 10: Summary of the hypotheses studied in this deliverable ... 46
Table 11: Model based average estimates of the transformed sqrt_percentil_neg_acc_5 for the different levels of Main effect and road type, together with Tukey multiple comparison results. ... 57
Table 12: Number of observations for cars and trucks with the non-haptic and haptic system. ... 57
Table 13: Overview of VMCs contributing to comparisons A to E using controlled data ... 59
Table 14: Overview of VMCs contributing to comparison A using naturalistic data ... 59

Table 15: Example of presentation of results (not real data, for illustration purposes only) 60
Table 16: Content of each dataset types 62
Table 17: Number of events and situations available for each comparison types analysis 63
Table 18: Content of the naturalistic dataset used to compare the ecoDriver nomadic systems with the normal driving situation (baseline) 64
Table 19: Summary of results for energy analysis 68
Table 20: Completed workload questionnaires per system type 70

Glossary of terms

Term	Description
App	In general: application software that causes a computer to perform tasks for computer users. In ecoDriver: the ecoDriver App.
Baseline period / phase	The part of the data collection during which the function(s) operate in "silent mode", that is, they collect data, but do not give any signals to the driver. From the viewpoint of the driver the function(s) is/are off.
CAN bus	A CAN bus (Controller Areas Network) is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other in applications without a host computer.
Controlled study	Study where the effect of a system is assessed based on a Baseline/Treatment comparison where pre-determined routes are scheduled for all participants.
Embedded system	An ecoDriver system that uses detailed vehicle data (CAN bus or OBD), i.e. an OEM system or a FeDS.
Event	An event is something that happens in a specific period of time which is individuated combining (pre-processed) measures according to predefined rules.
FeDS	The Full ecoDriver System.
FOT	A FOT (Field Operational Test) is a study undertaken to evaluate a function, or functions, under normal operating conditions in environments typically encountered by the host vehicle(s) using quasi-experimental methods
Function	Implementation of a set of rules to achieve a specified goal
Haptic system / feedback	In ecoDriver: using (variations in) gas pedal force as an HMI.
HMI	Human-Machine Interface. In ecoDriver, the HMI can have haptic, visual and auditory components.
HuD	Head-up-display
Hypothesis	A specific statement linking a cause to an effect and based on a mechanism linking the two. It is applied to one or more functions and can be tested with statistical means by analysing specific performance indicators in specific scenarios. A hypothesis is expected to predict the direction of the expected change.
Naturalistic Driving (ND)	Refers to studies undertaken using unobtrusive observation when driving in a natural setting.
ND	Naturalistic Driving
Nox	Nitrogen oxides
OBD	On Board Diagnostics
OEM	Original equipment manufacturer

Term	Description
Performance Indicator (PI)	Quantitative or qualitative indicator, derived from one or several measures, agreed on beforehand, expressed as a percentage, index, rate or other value, which is monitored at regular or irregular intervals and can be compared to one or more criteria.
PI	Performance Indicator
PKE	Positive kinetic energy
Research question	A research question is a general question to be answered by compiling and testing related specific hypotheses.
RPM	Revolutions per minute are a measure of the frequency of rotation, in ecoDriver context: the engine's rotational speed.
Scenario	A scenario is a use case in a specific situation.
Situation	One specific level or a combination of more specific levels of situational variables.
Situational Variable (SV)	An aspect of the surroundings made up of distinguishable levels. At any point in time at least one of these levels must be valid.
SV	Situational Variable
System	A system is a combination of hardware and software enabling one or more functions
THW	time headway
Treatment period / phase	The part of the data collection during which the function(s) are switched on by the experimental leader, such that they are either active all the time, or can be switched on or off by the driver.
TTC	time to collision
VMC	Vehicle Management Centre

Acronyms

Acronym	Description
CRF	Centro Ricerche Fiat
BMW	Bayerische Motoren Werke
VTI	Swedish National Road and Transport Research Institute
IKA	Institute for Automotive Engineering
CTAG	Automotive Technology Centre of Galicia
IFSTTAR	French institute of science and technology for transport, spatial planning, development and networks
TNO	Netherlands Organisation for Applied Scientific Research

1 Introduction

The ecoDriver project is broken down into five major sub-projects (SPs):
SP1: Supporting Drivers in eco-driving
SP2: Real-time Calculation of Energy Use and Emissions
SP3: Real-World Trials
SP4: Evaluation of Effectiveness
SP5: Scaling Up and Future-Casting

The ecoDriver project has tested nine different eco-driving support systems developed within the project (SP1&SP2) under real world driving conditions (SP3). The purpose of this deliverable is to present the results of the comprehensive evaluation of those trials, using the data from SP3. These SP4 results are then exploited by SP5 to predict the European-wide impact of the ecoDriver technologies (see D53.1 and D54.1 deliverable).

The ecoDriver systems differed from each other in the way advice was presented to the driver (visual or haptic, with or without auditory warnings), how the information was presented (what the 'screens' looked like), and on which information the advice was based. On some vehicles, the ecoDriver system had full access to the vehicles' data (CAN data); on other vehicles the system only had access to a limited amount of the vehicle information (OBD2 connection); or the ecoDriver system had no access to data coming from the vehicle. Some systems used map data while others did not. There were trucks, vans, buses, and cars involved in the trials. Most of the trials were carried out under 'controlled' conditions meaning that a pre-defined route was followed and an observer was present. Other trials, however, involved naturalistic driving in which no pre-defined route was followed and drivers drove where and when they wanted or, in the case of fleet drivers, where and when they were scheduled. Clearly no observer was present here except maybe for passengers joining the driver.

All these differences also resulted in different experimental set-ups. This was also necessary to accommodate local differences. The trials took place in seven countries (see Figure 1). Therefore it was, for example, necessary to take specific weather conditions into account (in Sweden for example there were trials with and without winter tyres).

Figure 1: Countries where the trials took place

The differences in systems, in type of experiments and experimental designs made the analyses of the collected data a difficult one. All the required[1] data was not always collected because of lack of availability of sensors. In addition, the same data (signal) could not always be collected with the same accuracy, and the data sets collected were not of equal size. And because of confidentiality not all comparisons could be made. Therefore, an analysis model had to be adopted that could deal with these differences and that could be adapted to different comparisons.

In this deliverable, we partly repeat information from previous deliverables to ensure that this deliverable can be read as a stand-alone document and that all the relevant information is present. However, we also clearly refer to already published project deliverables for more details to avoid too much overlap. We describe the different systems, the analysis model, the performance indicators used, and the comparisons that could be made. But the main focus of this deliverable is on the results of the analyses of the data collected in the real-world trials.

Reading this deliverable

The range of information and results that could be presented in this deliverable is enormous. The potential readers of this deliverable are likely to have diverse backgrounds and interests. We therefore needed to find a balance between information and readability. Presenting everything can be of interest to some but will diminish the readability for many. This deliverable starts therefore with an executive summary (Chapter 2). This summary can be read separately from the rest of the deliverable. The more detailed presentation of the results (including, e.g., description of systems and experimental designs) are presented in Chapters 3 through 10 on which the executive summary is based. There are three chapters on results: Chapter 6 presents the analyses on energy use, Chapter 7 covers attention and Chapter 8 describes the effects of the developed systems on driving behaviour. These each end with a

---

[1] Required from a hypothesis perspective.

summary of the results of that chapter, given that there are several hypotheses related to for example driving behaviour. The deliverable concludes with a discussion on the results (Chapter 9) and implications and lessons learned (Chapter 10). Accompanying this deliverable, there is a separate document that contains the annexes (Annex A through G). These annexes provide the detailed descriptions of the test centres (VMCs), the experimental designs used in each trial and detailed outcomes of the statistical analyses.

2 Executive summary

The ecoDriver project tested nine different eco-driving support systems developed within the project under real world driving conditions. The systems differed from each other, but so also did the vehicles used, the data collection systems, and the experimental plan for each trial. These differences made the analyses of the collected data a difficult one. All the required (from a hypothesis perspective) data was not always collected because of lack of availability of sensors. In addition, the same data (signal) could not always be collected with the same accuracy, and the data sets collected were not of equal size. And because of confidentiality not all comparisons could be made. Therefore, an analysis model had to be adopted that could deal with these differences and that could be adapted to different comparisons.

This deliverable reports the different experiments together with the system tested. We describe the common methodology that has been set up for the project, which is based on open source software (R Core Team (2015)). Results are provided in summary form, followed by detailed comments and discussions of the implications.

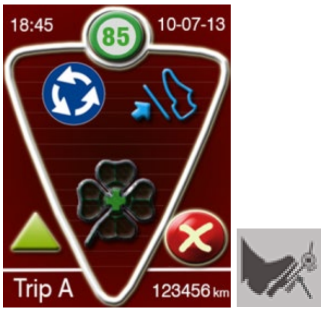
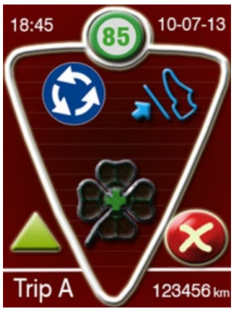
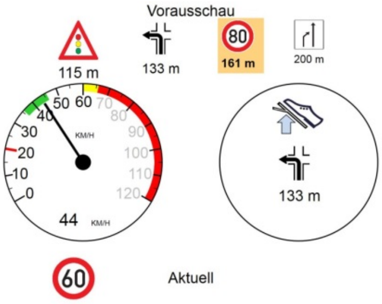
2.1 Overview of the systems and experimental designs

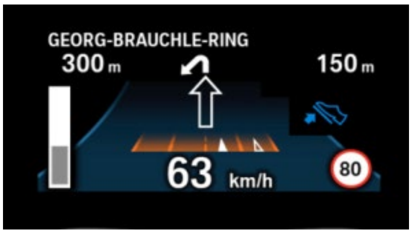
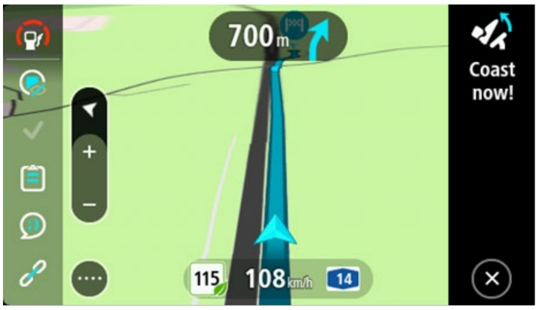
In total nine different systems were tested. A summary overview is presented in Table 1. Depending on performance of the driver or the advice provided for a specific event, the visual information looks different from the screen shots as presented in Table 1.

Systems are grouped into categories in order not to individualise OEM systems performances and so avoid benchmarking issues. Five different categories of systems have been identified and are also used for further statistical comparisons:

1. **Type A:** All ecoDriver tested systems are in this category. This allow for global comparisons. For the naturalistic data, this category only contains the TomTom system and the ecoDriver App.
2. **Type B:** This is the embedded systems category including CRF (1), CRF (2), CRF (4), CRF (5), Daimler, BMW, and the Full ecoDriver system (FeDS).
3. **Type C:** This is the Full ecoDriver system (FeDS), individualised as it is built within the ecoDriver project.
4. **Type D:** This is the ecoDriver App, individualised as it is built within the ecoDriver project.
5. **Type E:** All haptic systems belong to this category: CRF (2) and the Daimler system.

Table 1: The systems tested within the ecoDriver project

System	Screen shot	HMI / Information	Vehicle
CRF (1); Fiat Bravo prototype		Visual / CAN information / no map information	Passenger car
CRF (2); Alfa Romeo Giulietta prototype		Visual and haptic / CAN information / no map information	Passenger car
CRF (3); Alfa Romeo Giulietta prototype		Visual / CAN information / no map information	Passenger car
CRF (4); Lancia Musa prototype		Visual / CAN information / no map information	Passenger car
Daimler		Visual and haptic / CAN information / map information	Truck

System	Screen shot	HMI / Information	Vehicle
BMW	 	Visual (dashboard and HuD) / CAN information / map information	Passenger car
TomTom		Visual / OBD2 connection / map information	Trucks and vans
Leeds – TomTom system	No visual display	Auditory/FMS connection	Hybrid bus
ecoDriver App (IFSTTAR / CTAG)		Visual	Passenger cars
Full ecoDriver system (FeDS; CTAG, TNO)		Visual	Passenger cars (CTAG, VTI, IKA, IFSTTAR)

Both "controlled" drives, in which the vehicles were driven along a fixed route, and "naturalistic" drives (ND), in which vehicles were driven in normal daily use, were conducted in the project. Some vehicles were used in only one or the other type of driving. The experimental designs differed between the different test sites, as shown in Table 2. These differences had an impact on the complexity of the statistical analyses performed during the evaluation process. Indeed, due to the large number of test sites and their respective differences (number of test cars, number of routes, number of participants, experiment type), and also technical constraints, it was impossible to harmonise the designs. The statistical methods took these specificities into account as much as possible.

It is important to note that an observer was present in the experimental car for all the controlled drives. The purpose was to collect driving behaviour data such red light violations or overtakings with the help of a dedicated application. As an observer was present for both driving conditions (without and with the system), the analysis focused on the differences between these conditions with the presumption that any potential bias would be present in both conditions and that be neutralised. Ideally, of course, the need for such observation would be eliminated, but for the comment the use of an observer remains the most efficient and reliable means to collect the required extra information on driving performance.

Ideally too, the experimental design of all the trials would have been identical, e.g. for the various trials with the FeDS. It would also have been preferable for there to be naturalistic trials in all locations. However, this was no feasible because most of the vehicles were not homologated and could therefore only be used under controlled conditions. The project also had to use convenience samples in many locations, so that recruitment possibilities were limited. The use of a limited number of drives also prevented observation of how effectiveness developed over time, which is a very relevant topic in the investigation of eco-driving.

Table 2: Overview of the experimental design at the different test sites

Test site	Design	Number participants	Controlled / ND
CRF	Six drives per car; first drive baseline; the final drive of the Alfa Romeo Giulietta was without the haptic pedal; order of cars balanced across participants; participants completed all drives with one car before moving onto the next car	12 (CRF employees)	Controlled
Daimler	Three drives; baseline; visual; visual and haptic; Randomised order; due to the location of the route some drivers experienced the system before the test started. This was also balanced.	24	Controlled
BMW	Three drives; first baseline drive then two experimental drives	10 (BMW employees)	Controlled
TomTom (Trucks)	Baseline, previous TomTom eco-driving solution, system1, system2, system3[2]	10	ND

---

[2] The three systems differed in functionalities. All these new functionalities were developed in the eco-Driver project.

Test site	Design	Number participants	Controlled / ND
TomTom (LCVs)	Baseline, previous TomTom eco-driving solution, system1, system2, system32	10	ND
Leeds - TomTom	Baseline (with existing fleet-provided eco-driving and aggressive driving assistance system) (1), system (2)	Approx. 50-60	ND
FeDS (VTI)	Baseline (1), **Baseline (2)**, Instruction system (no driving), FeDS (1), FeDS (2), FeDS (3), **FeDS (4)**, FeDS (5), **Baseline (3)**, **Baseline (4)**[3]	12 (10 complete drives)	Controlled
FeDS (IKA)	Baseline, FeDS (1), FeDS (2)	18	Controlled
FeDS (CTAG)	Baseline (1), FeDS, Baseline (2)	30 (CTAG employees)	Controlled
ecoDriver App (CTAG)	Baseline (1), ecoDriver App, Baseline (2)	10 (CTAG employees)	Controlled
ecoDriver App (CTAG)	Baseline (1), ecoDriver App, Baseline (2)	10	ND
ecoDriver App (IFSTTAR)	Baseline (1), ecoDriver App, Baseline (2)	10	ND (plus a controlled drive)
ecoDriver App (IFSTTAR)	Baseline, ecoDriver App	20	Controlled

2.2 Hypotheses and analysis methods

An initial list of hypotheses was developed in an earlier stage of the project within the development of the assessment protocol (WP4.1). This list has evolved according to technical constraints, and some of them are addressed in Deliverable 54.1. The final list of hypotheses is presented in Table 4.

Some of these hypotheses are based on commonly used performance indicators, while others are based on an original ecoDriver approach. From the state of the art of eco-driving practices across Europe, four "golden rules" related to the driving behaviour have been identified and tested through hypotheses. The chosen rules used for the ecoDriver project results from a trade-off between statistical performances in predicting eco-driving behaviour (Ericsson, 2001; Andrieu and Saint Pierre, 2012), and their link to practical driving rules stated in the literature (see for example the CIECA report, 2007). Although these rules are not an absolute definition of eco-driving, they can be seen as a four dimension measure of eco-driving behaviour. These rules are detailed in Table 3.

---

[3] FeDS (1) – FeDS (5) are five different drives with the FeDS. Not all drives nor all baselines were used in the analyses. The bold ones were used in the analyses.

Table 3: ecoDriver "golden rules" of eco-driving and their respective performance indicator's (PI).

Instruction	**Performance Indicator (definitions in Table 8)**
Rule 1. Shift up as soon as possible: Shift up between 2.000 and 2.500 revolutions per minute.	Average engine speed at the shift into a higher gear.
Rule 2. Maintain a steady speed: Use the highest gear possible and drive with low engine RPM.	Index of gear ratio distribution and engine speed associated.
Rule 3. Anticipate traffic flow: Look ahead as far as possible and anticipate the surrounding traffic.	Positive Kinetic Energy.
Rule 4. Decelerate Smoothly: When you have to slow down or to stop, decelerate smoothly by releasing the accelerator in time, leaving the car in gear.	Percentage of time in engine brake.

It is worth noting that the PI based hypotheses also specify a direction for the expected change according to state of the art or previous studies. When the expected change is not known, this direction has not been specified in the hypothesis formulation.

Table 4: Summary of the hypotheses studied in this deliverable

Main section in deliverable	**Research Question category**	**Hypothesis number**	**Hypothesis**
Energy & emissions	ENERGY	1	Using an ecoDriver system will reduce the average fuel consumption Using an ecoDriver system will reduce the average CO2 emissions
		2	Using an ecoDriver system will reduce the average energy consumption
		3	Using an ecoDriver system will reduce the average NOx emissions
Driver workload and attention	WORKLOAD	4	Using an ecoDriver system will increase driver workload
		5	Workload varies across the different ecoDriver system types
	ATTENTION	6	Using an ecoDriver system (which provides in-trip feedback), drivers are more distracted
		7	In-car feedback from the ecoDriver system causes inappropriate/dangerous visual behaviour, in terms of glances towards the device

Main section in deliverable	Research Question category	Hypothesis number	Hypothesis
		8	Using an ecoDriver system, the driver will look more at the speedometer/rev counter
Driver behaviour	SPEED	9	Using an ecoDriver system the average velocity when cruising will be lower
		10	Using an ecoDriver system the average free velocity will be lower
	SPEED SITUATIONS		Using an ecoDriver system, speed will change when driving before/at locations where a low speed is recommended by the system, such as:
		11	Location: Intersections
		12	Location: Zebra crossings
		13	Location: Speed bumps
		14	Location: Sharp curves
		15	Location: Crest
		16	Location: Speed limit changes
	THW DISTANCE SITUATIONS	17	Using an ecoDriver system, the time headway distribution to leading vehicle will change
			Using an ecoDriver system, there will be shorter distances to vehicles before/at safety critical locations, such as:
		18	Location: Intersections
		19	Location: Zebra crossings
		20	Location: Speed bumps
		21	Location: Sharp curves
		22	Location: Crest
		23	Location: Speed limit changes
	EVENTS	24	Using an ecoDriver system, there will be more red or amber light violations
		25	Using an ecoDriver system, there will be fewer overtakings
		26	Using an ecoDriver system, there will be less overspeeding
	4 GOLDEN RULES	27	Using an ecoDriver system, the average rpm when shifting up will be reduced
		28	Using an ecoDriver system, the weighted average engine rpm will be decreased

Main section in deliverable	Research Question category	Hypothesis number	Hypothesis
		29	Using an ecoDriver system, the variability of speed profiles will be decreased
		30	Using an ecoDriver system, the use of the engine brake will be improved
	ACCEL/DECEL	31	Using an ecoDriver system, the acceleration distribution will change
		32	Using an ecoDriver system, the deceleration distribution will change
		33	Using an ecoDriver system, acceleration after being stationary will be less aggressive
	ACCEL/DECEL SITUATIONS		Using an ecoDriver system, the acceleration distribution will change before/at the following locations:
		34	Location: Intersections
		35	Location: Zebra crossings
		36	Location: Speed bumps
		37	Location: Sharp curves
		38	Location: Crest
		39	Location: Speed limit changes

The overall aim of the ecoDriver analysis is to address almost 40 well-defined hypotheses. Although many statistical analysis methods may exist to answer such questions, from the simplest to far more complex ones, a common scheme has emerged from previous experiences. Indeed, taking full profit from the richness of the data at its finest level (multiple 10 Hz sampled signals) is often a very difficult task. Practitioners rely instead on data reduction methods first, followed by more or less complex linear analysis (Analysis of Variance, Generalised Linear Mixed Models, etc.).

The evaluation approach is largely based on the FESTA Handbook (FESTA, 2014). The FESTA approach was applied in the design of the ecoDriver evaluation studies. In ecoDriver Deliverable D41.1 (Kircher et al., 2012), the steps from Research Questions to Hypotheses, to Performance Indicators, Measures and Sensors have been detailed. An overview of the preliminary steps to reduce data and obtain comparable aggregated tables is provided in Figure 2. The chosen aggregation method follows the recommendations of Dozza and Bärgman (2013).

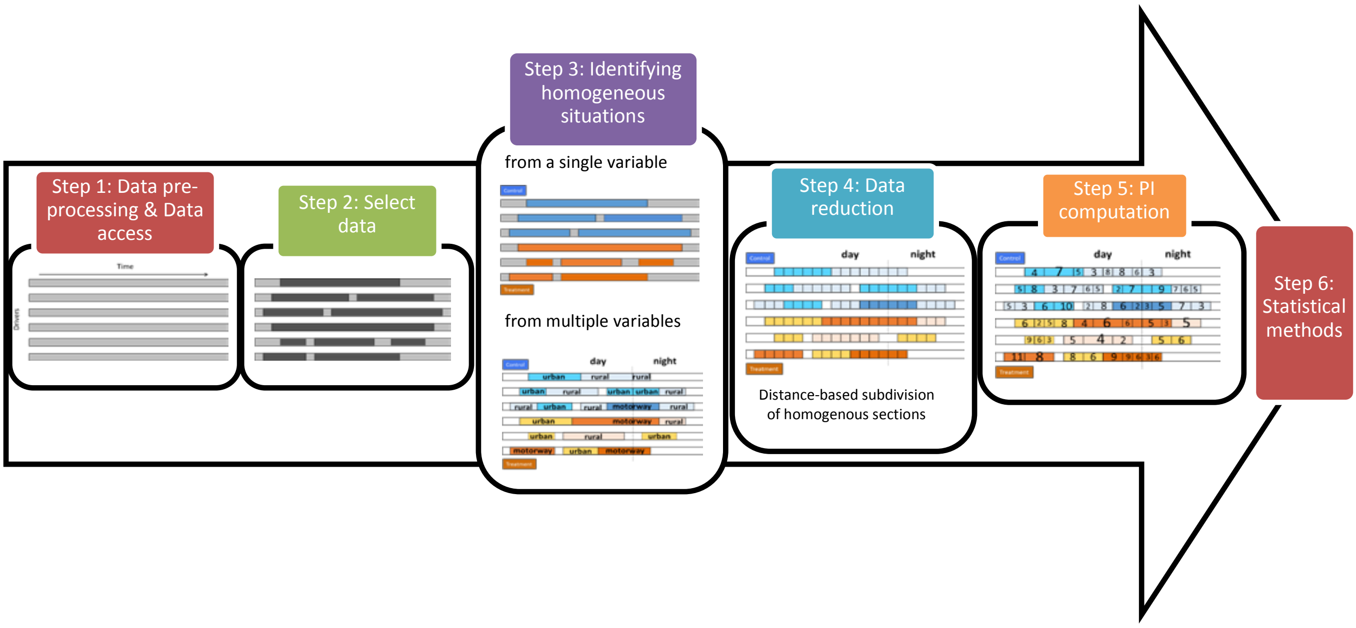


Figure 2: Overview of the data treatment and analysis process for a classical research hypothesis.

This general type of analysis is sometimes called **Aggregation based analysis (ABA).** This is a type of analysis for defining changes between baseline and treatment in terms of how driving performance changes over a range of traffic situations. The driving performance is evaluated through a suitable performance indicator (PI), directly linked to a specific research question. The selection of measures and PI has to reflect ideas on underlying driving behaviour, and in what way a change in the aggregate performance measure is predictive of a change in actual driving behaviour. As the ecoDriver systems should impact driving behaviour on various dimensions, a large number of performance indicators are used to study the impacts on travel efficiency, road safety, fuel consumption, and many other aspects. Usual statistical methods assumes observations are independent of each other, an assumption which does not suit Field Operational Test (FOT) data very well, as it will contain unavoidable driver-specific correlations (i.e. the driving style does not change between trips). To study interacting/confounding factors and to account for these driver specific correlations, more sophisticated statistical models need to be applied. One family of such models is “Generalised Linear Mixed Models” (GLMM). GLMM assumes correlated observations for the same driver, and that there is a random effect associated with each individual driver (i.e. one driver can be associated with higher and another with lower risk of event involvement). This has the additional advantage of allowing controlling for a small population of drivers being involved in a large proportion of safety events, something which indeed may become an issue (Dingus et al., 2006).

Statistical analyses were conducted using R, which is a free software environment for statistical computing and graphics (R Core Team, 2015; Hornik, 2015). A p-level of 0.05 was used to distinguish statistically significant effects. Using open source software allowed for the development of a harmonised common code, with the advantage of reducing errors.

In order to provide an answer to every research question, different data sets have been used. First of all, there are some specific data used for the driver attention studies. These data include questionnaires and eye tracker data that may not be described numerically.

A total of six different systems, and several additional sub-versions, have been evaluated within the ecoDriver project. For industrial confidentiality reasons, it is only possible to treat the full ecoDriver system (FeDs) and the ecoDriver App as individual systems; the others were merged into three different categories (All systems, Embedded systems, Haptic systems), each one of them being associated with a corresponding baseline. These constraints lead to the statistical comparisons depicted in Figure 3.

Energy related and driver behaviour hypotheses share the same analysis framework based on studying specifically a set of comparisons, from the more global to the more specific. Figure 3 presents the main comparisons, with the corresponding name of the dataset. Each data set type is different because it is linked to different VMCs and systems. The Embedded systems (Type B) are the OEM systems and the FeDS, i.e. systems that use detailed vehicle data from the CAN bus or OBD2. In contrast, the ecoDriver App (type D) does not use such detailed vehicle data. Further, it is worth noting that only the first global comparison can be assessed using naturalistic driving data.

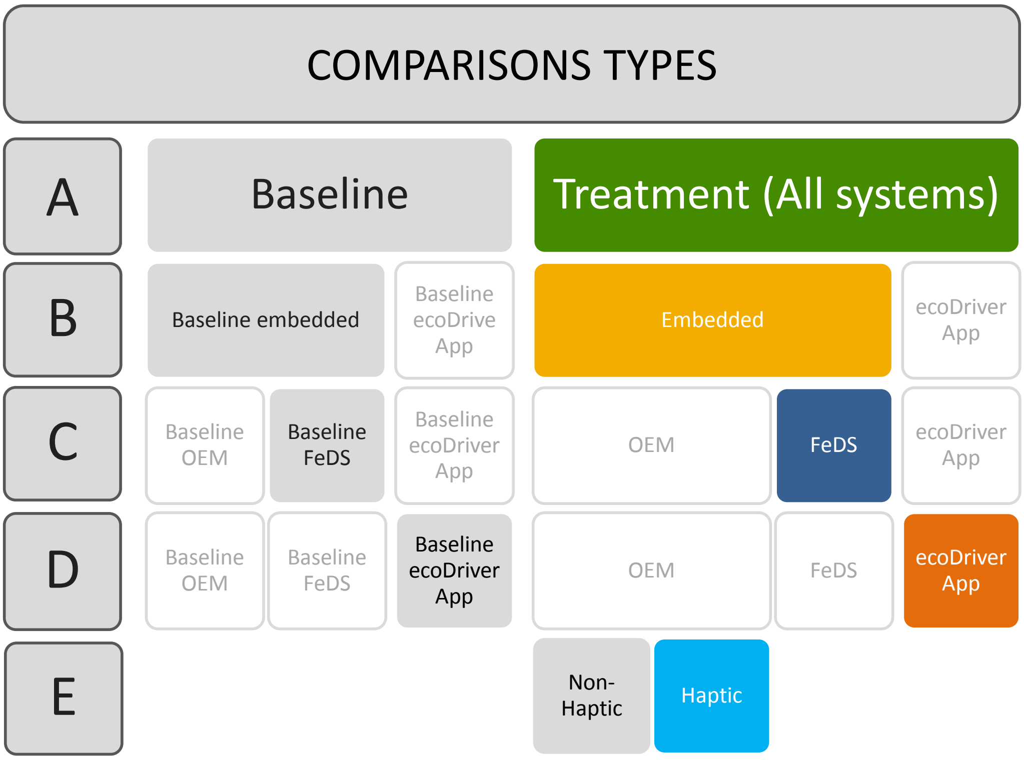


Figure 3: Overview of comparison types A through E

For comparison types A through D, the analysis consisted of *baseline versus treatment*, i.e. without versus with the given system(s). For comparison Type E, the comparison was *with versus without haptic feedback*, i.e. a system that included haptic feedback versus the same system without haptic feedback. (but both always have visual feedback). Each research question presented in Table 10 is therefore analysed for each of the five comparisons (Type A to E) using controlled data. Additionally, the Type A comparison is studied using only naturalistic data. The naturalistic data set does not contain any data from the TomTom trial due to strong indications that the trial results were contaminated by external factors, in particular differing levels of traffic congestion between the baseline and treatment periods. The various comparison types lead to a total of six different comparisons for each research question.

2.3 Overview of results

After a careful statistical analysis, numerous results from paired comparisons have been obtained for almost 40 different research questions. They are displayed in a summarised form below. The results reported below are *statistically significant* differences. When no statistical difference is found, it does not mean that there is in reality no effect. It can also mean that the power of the test is not strong enough to show reliably a statistical difference. Significant results are colour-coded. Green indicates a positive effect when using the ecoDriver systems, while red indicates a negative effect. The darker the green or red, the stronger is the effect. No colour indicates a non-significant difference. For example, looking at hypothesis 10 about changes in the average free speed, green cells indicates are indicating a significant decrease of the average free speed, and therefore a safer and eco-friendly driving behaviour.

Note that, for the naturalistic trials, results are missing simply because we do not have precise map information, and so we were unable to extract situations (intersections, traffic lights, speed bump etc.). Also, note that there was no radar on the vehicles in the naturalistic trials, so that no measure of time headway was possible.

Table 5: Summary of results for all the hypotheses tested using a PI based approach. Significant cells are coloured from red (negative impact) to green (positive impact).

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**Naturalistic (App) Type A**
1 Energy	% of reduction for fuel consumption & CO2	Urban	2.58	2.98	-1.28 (N.S.)	1.54 (N.S.)	3.12 (N.S.)	-1.57 (N.S.)
		Rural	5.76	6.03	2.66	3.15 (N.S.)	2.83 (N.S.)	-2.49 (N.S.)
		Motorway	2.21 (N.S.)	2.24 (N.S.)	1.53 (N.S.)	-	-	0.3 (N.S.)
		All road types	4.2	4.38	1.46	2.54	2.73 (N.S.)	-0.8 (N.S.)
2 Energy	% of energy consumption reduction[4]	Urban	-	-	-9.24 (N.S.)	-	-	-
		Rural	-	-	3.16 (N.S.)	-	-	-
		Motorway	-	-	6.72 (N.S.)	-	-	-
		All road types	-	-	-0.38 (N.S.)	-	-	-
3 Energy	% of NoX reduction compared to resp. baseline	Urban	2.61	3.27	1.64 (N.S.)	-0.28 (N.S.)	1.77 (N.S.)	-1.07 (N.S.)
		Rural	5.11	5.65	4.09	2.35 (N.S.)	0.1 (N.S.)	-0.9 (N.S.)
		Motorway	3.29	3.34	2.79 (N.S.)	-	-	3.44
		All road types	4.04	4.49	3.18	1.34 (N.S.)	0.67 (N.S.)	0.97 (N.S.)

---

[4] This hypothesis relates to electric vehicle energy use only, as collected in one of the controlled trials of the FeDS system.

Effect sizes in percentages (differences in % from relevant baseline)

Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	Naturalistic (App) Type A
9 Speed	Average speed when cruising	Urban	-2.79	3.30	4.76	-8.86 (N.S.)	3.63	3.28
		Rural	4.04	1.82	1.71 (N.S.)	2.17 (N.S.)	-0.95 (N.S.)	0.03 (N.S.)
		Motorway	3.42	3.32	3.50	-	-	1.25
		All road types	2.39	2.53	2.95	-	0.74 (N.S.)	1.24
10 Speed	Average speed when freely driving	Urban	3.07 (N.S.)	10.61	9.83	0.45 (N.S.)	-11.87 (N.S.)	-
		Rural	3.55	0.37 (N.S.)	0.37 (N.S.)	1.31 (N.S.)	-0.05 (N.S.)	-
		Motorway	0.57 (N.S.)	0.67 (N.S.)	0.62 (N.S.)	-	-	-
		All road types	2.97	4.06	2.78	1.18 (N.S.)	4.84 (N.S.)	-
11 Speed Situations	avg_speed_distance_based before intersections	Urban	-3.14	-0.13 (N.S.)	2.76	-1.4 (N.S.)	1.1 (N.S.)	-
		Rural	5.60	3.47	1.82	1.78	1.22 (N.S.)	-
		Motorway	5.08	5.01	2.57	-	-	-
		All road types	1.32	1.66	1.58	-0.61 (N.S.)	1.00	-
12 Speed Situations	avg_speed_distance_based before zebra crossings	Urban	-0.99 (N.S.)	2.33	4.18	0.49 (N.S.)	0.07 (N.S.)	-
		Rural	13.13	2.43 (N.S.)	3.47 (N.S.)	3.18	-1.83 (N.S.)	-
		Motorway	7.6 (N.S.)	7.58 (N.S.)	7.19 (N.S.)	-	-	-
		All road types	1.29	2.22	3.53	0.59 (N.S.)	-0.08 (N.S.)	-
13 Speed Situations	avg_speed_distance_based before speedbumps	Urban	1.1 (N.S.)	2.26 (N.S.)	1.32 (N.S.)	0.6 (N.S.)	-6.61 (N.S.)	-
		Rural	0.99 (N.S.)	1.65 (N.S.)	1.88 (N.S.)	-0.12 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	0.77 (N.S.)	1.46 (N.S.)	0.37 (N.S.)	-0.12 (N.S.)	-6.61 (N.S.)	-
14 Speed Situations	avg_speed_distance_based before sharp curves	Urban	-2.38 (N.S.)	1.35 (N.S.)	1.85 (N.S.)	3.26 (N.S.)	4.96	-
		Rural	3.72	2.45	3.40	1.35 (N.S.)	-1.46 (N.S.)	-
		Motorway	0.44 (N.S.)	0.22 (N.S.)	5.1 (N.S.)	-	-	-
		All road types	1.33	1.83	2.24	-0.79 (N.S.)	1.18 (N.S.)	-
15 Speed Situations	avg_speed_distance_based at crests	Urban	0.87 (N.S.)	0.94 (N.S.)	0.69 (N.S.)	2.25 (N.S.)	2.5 (N.S.)	-
		Rural	1.25 (N.S.)	1.08 (N.S.)	0.34 (N.S.)	2.16	1.18 (N.S.)	-
		Motorway	-2.66 (N.S.)	-2.65 (N.S.)	-2.62 (N.S.)	-	-	-
		All road types	1.68	1.59 (N.S.)	1.29 (N.S.)	2.21	1.06 (N.S.)	-
16 Speed Situations	avg_speed_distance_based before speed limit changes	Urban	1.41 (N.S.)	2.54 (N.S.)	4.2 (N.S.)	3.08 (N.S.)	1.14 (N.S.)	-
		Rural	2.30	2.36	2.35 (N.S.)	0.74 (N.S.)	-2.67 (N.S.)	-
		Motorway	6.42	6.31	4.24	-	-	-
		All road types	2.56	2.98	3.06	1.45 (N.S.)	-1.23 (N.S.)	-

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**Naturalistic (App) Type A**
17 THW Situations	Average time headway	Urban	6.50	11.15	12.23	3.97 (N.S.)	-	-
		Rural	5.86	5.65 (N.S.)	4.71 (N.S.)	-1.88 (N.S.)	-	-
		Motorway	8.56	9.17	12.36	-	-	-
		All road types	6.29	9.06	10.24	-0.33 (N.S.)	4.45 (N.S.)	-
18 THW Situations	Average time headway before intersections	Urban	8.10	12.93	13.87	3.67 (N.S.)	-	-
		Rural	2.6 (N.S.)	4.58	5.45 (N.S.)	-7.63 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	5.63	9.57	10.36	-1 (N.S.)	15.23	-
19 THW Situations	Average time headway before zebra crossings	Urban	-1.42 (N.S.)	2.87 (N.S.)	1.95 (N.S.)	-2.11 (N.S.)	-	-
		Rural	1.67 (N.S.)	-3.1 (N.S.)	-3.54 (N.S.)	4.45 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	-1.13 (N.S.)	1.42 (N.S.)	0.32 (N.S.)	-1.74 (N.S.)	11.64 (N.S.)	-
20 THW Situations	Average time headway before speed bumps	Urban	6.77 (N.S.)	8.12 (N.S.)	8.12 (N.S.)	6.47 (N.S.)	-	-
		Rural	0.32 (N.S.)	-6.8 (N.S.)	-6.8 (N.S.)	8.06 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	4.49 (N.S.)	0.69 (N.S.)	0.69 (N.S.)	6.33 (N.S.)	-	-
21 THW Situations	Average time headway before sharp curves	Urban	4.62 (N.S.)	16.54	22.27	0.56 (N.S.)	-	-
		Rural	7.87 (N.S.)	3.73 (N.S.)	2.73 (N.S.)	8.37 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	4.73 (N.S.)	8.36	8.68	1.32 (N.S.)	-	-
23 THW Situations	Average time headway before speed limit changes	Urban	7.19	13.95	16.80	5.59 (N.S.)	-	-
		Rural	3.79 (N.S.)	3.42 (N.S.)	3.39 (N.S.)	-0.36 (N.S.)	-	-
		Motorway	11.36 (N.S.)	12.24 (N.S.)	17.8 (N.S.)	-	-	-
		All road types	5.43	8.22	9.70	1.33 (N.S.)	-	-
27 Golden rules	Average rpm when shifting gear up	Urban	-0.73 (N.S.)	5.63	6.68	7.34	3.76 (N.S.)	3.85
		Rural	11.44	9.97	12.23	7.43	1.35 (N.S.)	8.29
		Motorway	3.19	3.42	3.32	-	-	2.19
		All road types	7.09	7.14	7.90	8.03	1.92 (N.S.)	2.97
28 Golden rules	weighted average engine rpm	Urban	2.48	9.12	9.39	7.70	-0.99 (N.S.)	7.13
		Rural	14.43	13.95	14.20	6.00	0.89 (N.S.)	9.12
		Motorway	4.15	4.41	3.72	-	-	2.24 (N.S.)
		All road types	9.64	10.24	9.46	7.03	0.42 (N.S.)	5.00

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**Naturalistic (App) Type A**
29 Golden rules	Positive kinetic energy	Urban	6.25	3.23	3.17	1.45 (N.S.)	0 (N.S.)	1.56 (N.S.)
		Rural	1.72	5.00	3.51	0 (N.S.)	1.54 (N.S.)	0 (N.S.)
		Motorway	0 (N.S.)	0 (N.S.)	0 (N.S.)	-	-	0 (N.S.)
		All road types	3.39	3.39	1.79	0 (N.S.)	1.52 (N.S.)	1.69
30 Golden rules	Percentage of driving time with engine brake	Urban	-2.89 (N.S.)	1 (N.S.)	2.15 (N.S.)	1.96 (N.S.)	-2.86 (N.S.)	-0.71 (N.S.)
		Rural	5.13	1.48 (N.S.)	5.11	6.38	-5.61 (N.S.)	3.73 (N.S.)
		Motorway	1.89 (N.S.)	2.24 (N.S.)	2.15 (N.S.)	-	-	-4.73
		All road types	1.83	1.17 (N.S.)	3.29	4.90	-5.11	-0.54 (N.S.)
31 Accel Decel	95th percentile positive acceleration	Urban	13.12	8.54	5.17	2.11 (N.S.)	-4.38 (N.S.)	4.77
		Rural	4.43	13.21	8.42	1.61 (N.S.)	3.59 (N.S.)	3.06 (N.S.)
		Motorway	-1.2 (N.S.)	0 (N.S.)	5.8 (N.S.)	-	-	7.44 (N.S.)
		All road types	8.10	9.81	6.57	1.12 (N.S.)	-0.09 (N.S.)	4.57
32 Accel Decel	5th percentile negative acceleration	Urban	11.34	5.11	6.45	0.65 (N.S.)	0 (N.S.)	3.88
		Rural	3.64	14.65	7.14	-1.54 (N.S.)	4.65 (N.S.)	3.28 (N.S.)
		Motorway	0 (N.S.)	0 (N.S.)	3.7 (N.S.)	-	-	7.38
		All road types	7.46	9.02	5.80	-1.05 (N.S.)	1.92 (N.S.)	4.31
33 Accel Decel	maximum acceleration after stationnary	Urban	2.22	2.94	0.7 (N.S.)	1.77	-4.21 (N.S.)	-
		Rural	-	-	-	-	-	-
		Motorway	-	-	-	-	-	-
		All road types	-	-	-	-	-	-
34 Accel Decel Situation	95th percentile of the negative acceleration before intersections	Urban	4.95	4.74	3.94	-0.09 (N.S.)	3.50	-
		Rural	-0.94	4.38	3.64	-1.42 (N.S.)	1.01 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.12	4.59	3.84	-	-	-
35 Accel Decel Situation	95th percentile of the negative acceleration before zebra crossings	Urban	2.39	2.61 (N.S.)	4.19 (N.S.)	0.76 (N.S.)	5.25 (N.S.)	-
		Rural	-11.03	6.51 (N.S.)	15.75	-7.55 (N.S.)	-2.84 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	1.53	3.07	5.72	0.56 (N.S.)	4.30	-
36 Accel Decel Situation	95th percentile of the negative acceleration before speed bumps	Urban	6.43	10.95	16.96	4.49	2.06 (N.S.)	-
		Rural	12.37	12.82	12.89	11.98	-	-
		Motorway	-	-	-	-	-	-
		All road types	7.02	11.06	15.40	4.91	-	-

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**Naturalistic (App) Type A**
37 Accel Decel Situation	95th percentile of the negative acceleration before sharp curves	Urban	3.44	4.09	1.96 (N.S.)	-0.7 (N.S.)	8.24	-
		Rural	4.25	5.41	4.13	0.78 (N.S.)	1.27 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.88	4.80	3.28	0.18 (N.S.)	4.51	-
38 Accel Decel Situation	95th percentile of the negative acceleration at crests	Urban	0.65 (N.S.)	0.66 (N.S.)	0.59 (N.S.)	-	-	-
		Rural	4.18 (N.S.)	5.62	5.48 (N.S.)	-1.57 (N.S.)	-3.75 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.44	4.31	3.89	-	-	-
39 Accel Decel Situation	95th percentile of the negative acceleration before speed limit changes	Urban	1.42 (N.S.)	2.57 (N.S.)	2.87 (N.S.)	-2.01 (N.S.)	8.24	-
		Rural	4.11	4.94	1.69 (N.S.)	0.21 (N.S.)	1.27 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	2.96	3.83	2.09 (N.S.)	-0.4 (N.S.)	4.51	-

The main findings are presented below; for each research question category (energy and emissions, driver workload and attention, etc.), three sets of results are presented. The first reports the combined effects of all the ecoDriver systems, the second provides a comparison across road types and the third details the comparison of different system categories (embedded versus nomadic for example). The exception to this are the results for workload and attention, which are presented more globally due to the data collection methodology; in addition the scarcity of event-based data (overtaking and violations) meant that these were not subjected to this pattern of analysis.

2.4 Main findings — energy and emissions

ENERGY

- Using an ecoDriver system will reduce the average fuel consumption & CO2 emission (per 100km).
- Using an ecoDriver system will reduce the average NOx emissions (per 100km).
- Using an ecoDriver system will reduce the average energy consumption (per km or 100km).

i. **Across all systems,** reductions in fuel consumption and CO_2 have an average value of 4.2%, considering different road types they ranged from 2.2% (non-significant reduction of energy on motorways where the sample is smaller) to 5.8% (significant reduction of energy on rural roads). Reductions in NOx emissions have a similar average value of 4% and are significant on all road types ranging from 2.6% (urban) to 5.1% (rural). In the naturalistic data, a significant reduction of NOx emissions of 3.4% on motorways is found.

ii. **Comparing the results across road types**, the ecoDriver systems reduced fuel consumption and CO_2 emissions by up to 5.76% (urban), with more impact on rural roads (5.8%). The same tendency for a bigger impact on rural roads is present on NOx reduction, with saving up to 5.1% on rural roads.

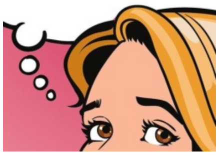
iii. **When grouping the systems by categories** the ecoDriver embedded systems (which use detailed vehicle data from the CAN bus or OBD2) perform better than the App, with fuel savings of up to 6% and NOx up to 5.7% on rural roads. Individually, the FeDS has a significant impact on both fuel/CO_2 and NOx with an average savings of up to 1.5% and 3.2% respectively and with saving up to 2.7% and 4.1% in rural condition. The App reduces significantly fuel consumption on average by 2.5%. The haptic systems in addition to visual system reduces fuel consumption by up to 3%. The hybrid bus system had no significant impact on fuel consumption, although there was a non-significant tendency for fuel consumption to reduce during system use.

2.5 Main findings — driver workload and attention

WORKLOAD

- When using an ecoDriver system, driver workload will increase
- Workload varies across the different ecoDriver system types

There was no evidence to suggest that any of the ecoDriver systems tested caused a substantial increase in subjective driver workload. Across all system types, there was only a very small increase in total workload when interacting with the system, with some tentative evidence to suggest that workload may decrease with increasing exposure.



ATTENTION

- Using an ecoDriver system with in-trip feedback, the drivers are more distracted
- In-car feedback from the ecoDriver system cause inappropriate/dangerous visual behaviour, in terms of glances towards the device
- Using an ecoDriver system, the driver will look more at the speedometer/rev counter

Most systems tested have a visual user interface aimed to attract visual attention. Attentional effects were investigated with only the FeDS. The overall time spent looking away from the forward roadway was found to be larger with the FeDS. However, drivers did not neglect to glance at the mirrors or speedometer, and data obtained from motorway driving indicate that glances towards the FeDS did not exceed the available visual spare capacity as determined via a visual occlusion study. Glance patterns indicated that drivers were anticipating feedback from the FeDS, which indicates the HMI can be improved to reduce workload. Thus, it is advisable to integrate the eco-support system with the speedometer.

2.6 Main findings — driver speed

SPEED

- Using an ecoDriver system the average velocity when cruising will be lower
- Using an ecoDriver system the average free velocity will be lower
- Using an ecoDriver system, speed will change when driving before locations where a low speed is recommended by the system

i. **Across all systems,** cruising speed in the controlled drives reduced by 3.4% on the motorway and 4% on rural roads. The naturalistic data also show a reduction in cruising speed, by up to 3.3%. Average speed when free driving is reduced by about 3% for the controlled studies only. Speed reduced in advance of intersections and speed limit decreases in rural and motorway conditions. Speed reduced before sharp curves and zebra crossings in rural conditions.

ii. **Comparing the results across road types,** speed reductions were observed mostly on rural roads and motorway for the controlled drives (4% and 3.4% respectively), with a similar reduction (3.3%) observed for the naturalistic data on urban roads. Potential benefits exists for both rural and urban road types when systems alert for infrastructure constraints.

iii. **When grouping the systems by categories** the embedded systems provide strong evidence of a cruising speed reduction of 1.5% to 3.5% in all conditions, while the App does not show any significant effect. The haptic systems obtained an *additional* 3.6% reduction. A reduction of cruising speed of 8.5% on urban roads is found. Free driving speed is also reduced by around 10% in urban areas with the embedded systems. Around events, the embedded systems showed speed reductions of up to 6.3%, with the largest effects observed before a speed limit change and on the approach to intersections.

2.7 Main findings — time headway

THW DISTANCE / SITUATIONS

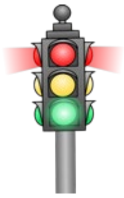
- Using an ecoDriver system, the time headway distribution to leading vehicle will change
- Using an ecoDriver system, there will be shorter distances to vehicles before safety critical locations

i. **Across all systems,** time headway increased on average by 6.3%. The systems had no impact before zebra crossings, speed bumps and crests, but time headway increased by up to 8.1% before intersections. The systems also increased time headway before speed limit changes by 5.4%.

ii. **Comparing the results across road types,** average time headway increased globally for every road type. Overall effects on time headway were particularly strong for motorways for the FeDS. Before intersections, haptic systems show the greatest effects on all road types (15.2 %).

iii. **When grouping the systems by categories** benefits came only from the embedded systems and for the FeDS itself, increasing average time headway by up to 22.3% on sharp urban curves. Those systems without radar (ecoDriver App and the haptic systems) were unable to have an effect. Significant impacts were observed and before intersections (13.9 %), sharp curves (22.3 %), and speed limit changes (16.8 %).

2.8 Main findings — driver behaviour in events



EVENTS

- Using an ecoDriver system, there will be more red or amber light violations
- Using an ecoDriver system, there will be fewer overtakings

Events such as red or amber light violations during the controlled trials proved very difficult to observe in a reliable way. The number of overtaking manoeuvres were observed at an identical rate in baseline and treatment phases, while less speeding events were observed when using embedded systems.

2.9 Main findings — the four golden rules

4 GOLDEN RULES

- Using an ecoDriver system, the average rpm when shifting up will be reduced
- Using an ecoDriver system, the weighted average engine rpm will be decreased
- Using an ecoDriver system, the variability of speed profiles will be decreased
- Using an ecoDriver system, the use of the engine brake will be improved

i. **Across all systems,** in the controlled drives, positive impacts on the rules of eco-driving are observed, by up to 9.7%. The use of the engine brake improved only on rural roads. Results are more variable for the naturalistic drives, but still overall positive for average rpm when shifting up (3%), weighted average engine rpm (3% and PKE (5%).

ii. **Comparing the results across road types,** in the controlled drives, positive effects of the systems are observed on every road type, although weaker on motorways. No significant change is observed in engine brake use for urban and motorways. Even for embedded systems, there is no significant change on speed profiles on motorways.

iii. **When grouping the systems by categories** the haptic system does not induce any changes whilst the embedded systems, including FeDS, succeeded in generating driving behaviour compliant with the golden rules. The ecoDriver App also generated green driving behaviour, but less saliently than the embedded systems. The use of the engine brake increased with both the FeDS (5.1%) and the App (6.4%), but only for rural roads. The App tested under naturalistic driving conditions is effective for all rules, except for the use of engine brake.

2.10 Main findings — acceleration and deceleration

ACCEL DECEL / SITUATIONS

- Using an ecoDriver system, the high accelerations will be reduced
- Using an ecoDriver system, the hard deceleration will be reduced
- Using an ecoDriver system, acceleration after being stationary will be less aggressive
- Using an ecoDriver system, the acceleration distribution will change before locations where a low speed is recommended by the system

i. **Across all systems,** there are improvements in acceleration: a change of about 10% was found in reducing 95th percentile of acceleration, 5th percentile of deceleration, and maximum acceleration. The naturalistic data deliver a different picture: high accelerations and decelerations are reduced on urban roads, but they are increased on rural roads and motorways. Once again, the main benefits are observed for embedded systems, and for urban and rural roads. Neither the haptic systems nor the App softened deceleration before specific situations.

ii. **Comparing the results across road types,** large benefits can be expected on urban and rural roads, but not on motorways. For deceleration at the specific situations, the impacts are similar for urban and rural roads. The observed changes are more linked to the situation type than to the road type itself.

iii. **When grouping the systems by categories,** neither the App nor the haptic variant generated any significant benefits. In controlled drives, only the embedded systems generated softer acceleration and deceleration. The nomadic eco-driving systems had an impact when used in naturalistic driving in urban areas. For deceleration at the specific situations, the main benefits come from the embedded systems such as the FeDs.

2.11 Overall conclusions

Within ecoDriver, several different systems were tested with different characteristics and features. The only systems we can isolate are the ones developed solely within the project: the FeDS and the ecoDriver App. These two systems are very different despite the apparently similar HMI. Other systems do not share the same HMI nor the same approach to encouraging eco-driving behaviour.

As a global picture of the ecoDriver results, it is confirmed that embedded systems (including FeDS), provide more benefits than nomadic systems such as the App. Embedded systems perform better because of their integration into the vehicle and the ability to use vehicle data information to display advice. On the other hand, non-embedded systems such as the App rely on internal computation mainly based on GPS information. It is therefore not surprising to observe this difference. Adding a haptic pedal can be useful, and produces small benefits, in the direction of greener driving. Although usually non-significant, these results confirm that such a feature can be an important element of a larger system, and can increase acceptability. The poor performance of the App on controlled drives is counterbalanced by some positive results during the naturalistic experiment, especially in saving energy.

2.11.1 Energy and emissions

On average, the systems tested achieved a reduction of emissions and energy consumption ranging from 2.2% to 5.8%. It is encouraging to note that some of the non-significant results for the App during the controlled drives can be turned into significant ones when used in a naturalistic setting. This could be considered as evidence that such systems require familiarisation. The best results in diminishing consumption and emissions are achieved in rural roads, perhaps due to there being less variation in traffic conditions and infrastructure.

2.11.2 Safety (speed, time headway, accelerations)

The effect of eco-driving on safety is not yet very well known, despite the usual idea that a smooth and smart driving style should increase safety. The ecoDriver experiments did not allow for observations of real crashes, and therefore rely on analysing speed, acceleration, and time headway, so-called surrogate safety measures.

When the ecoDriver system included a clear indication of the recommended green speed (embedded systems), the average speed when cruising is reduced by around 2% to 4%. A speed reduction of up to 10% was also observed for free driving in urban conditions. Similar effects are not observed for the ecoDriver App. This can be explained by the absence of a green speed indication. The ecoDriver App only displayed the current speed limit, moreover, it is implemented in a different way than usual (for the App, the colour of the speedometer was green before the speed limit, and red after it). This information has apparently no impact on the way users of the App manage their speed.

With regards to driver behaviour at specific situations which may pose a safety problem (intersections, zebra crossings, speed bumps, sharp curves, hill crests and speed limit reductions), when using ecoDriver systems, speed is also decreased. All the systems alerted when approaching an intersection and all of them also provided information about the current speed limit to the driver. In advance of these last two situations, there is evidence of a decrease in speed for the embedded systems, and also the FeDS. For both haptic systems and the ecoDriver App, taken alone, no statistically significant reduction in speed was found.

A significant reduction in speed is also observed before sharp curves on rural roads when using an embedded system. Almost no effect was found before speed bumps and at crests for all the systems together. These results allow us to derive the following two conclusions:

- When not announced, specific situations are not taken into account by the driver.
- When announced, specific situations generate a change in speed behaviour. This change is closely related to the quality of the system (integration, precision, reliability, HMI).

Time headway (THW) is another safety measure. The impact of the systems on THW follows the same pattern as for speed. THW increased on average by between 6% and 10% for all road types, and for embedded systems only. Once again, the ecoDriver App and the haptic variant failed to reach significance despite the positive direction of the results. Strong effects are also observed before intersections and speed limit changes for all the systems. Although the App and haptic systems did not reach significance, their results are in a positive direction. It is worth noting the strong impact of the embedded systems before speed limit changes on all road types. From these results, we can confirm that when the driver is not alerted about an upcoming situation, he or she will react in the usual way. In other words, there is no carry-over effect of using an ecoDriver system. When advised by the system, these situations are handled in a much safer way than without the system advice.

When considering accelerations and decelerations, they are decreased when using an embedded system on urban and rural roads. Other conditions failed to reach significance. Intersections proved to be well anticipated by drivers, with smooth decelerations. Despite the absence of an alert from the systems, zebra crossings and speed bumps were also very well anticipated. Globally, the significance is better than for the speed results. The variability of the acceleration signal is much greater than the variability of speed. It is therefore more difficult to detect a change in average speed than on 95th percentile of acceleration. The exception is when an effect on speed is expected, such as being alerted to a speed change: here we observe less impact on accelerations than on speed. Results for the naturalistic part of the data are once again contradictory. Accelerations and decelerations are smoother on urban roads than for the controlled studies, while they are harsher on motorways. The reason for this observation is not clear.

2.11.3 Golden rules of eco-driving

All the systems tested, except the haptic version, induced positive effects on the four indicators characterising eco-driving. The embedded systems induced larger benefits than the App. The results prove that the ecoDriver systems generally induce the following driving behaviour:

i. shifting gear up more quickly,
ii. driving with a lower engine rpm,
iii. smoother speed profiles and
iv. increased usage of engine brake.

Among these indicators, the smoothness of the speed profiles is more correlated with fuel consumption. All these different aspects of the change in driving should translate into energy reduction and safer behaviour. But when eco-driving is only partially applied, most of the benefits can be lost.

The application of the eco-driving golden rules is significant for all four rules on rural roads only; therefore it is not surprising that significant fuel savings are obtained for this road type. Applying the golden rules on urban roads is difficult because there are many constraints related to safety that are a priority for the driver. Eco-driving in urban areas can become closer to safe driving than green driving. On the other hand, there are very few constraints on motorways, and driving there is usually smooth. It seems difficult to apply some of the eco-driving rules (use engine brake for example) that can help save fuel. This explains the non-significant results obtained for energy savings on motorways.

Results obtained for naturalistic data are encouraging because significant positive effects are obtained, even when it is not the case for controlled experiment (overall effect of rule 3). Drivers are less compliant with the golden rules, but still in the correct direction. Gear shifting behaviour is improved for naturalistic drivers, although it does not translate into significant fuel savings. Flattened speed profiles and increased use of the engine brake are not observed for the naturalistic data set, but results are similar to the controlled experiment. These last two rules may be difficult to apply using the ecoDriver HMI.

The main findings of this study can be summarised as follows:

- Using ecoDriver systems in real conditions, and applying a conservative statistical approach, energy savings range from 2% to 6%. This is less than aimed, but closer to the reality.

- The ecoDriver systems proved to have strong positive impacts on speed, time headway, and accelerations and decelerations. This could translate into less severe crashes.
- The ecoDriver systems proved to generate a driving style compliant with the golden rules of eco-driving.
- Advice on eco-driving in specific situations generates a change in driving behaviour. This change is closely related to the quality of the system (integration, precision, reliability, HMI).
- Nomadic systems change the driving behaviour in a good direction, but benefits are smaller than when using an embedded system.
- The naturalistic experiments gave different results than the controlled studies. Although not comparable (only the App was part of the two types of studies), these differences deserve deeper investigation.
- Naturalistic experiments are recommended to study the long-term impact of eco-driving. Driving style change is observed even when using a nomadic system, safety or energy benefits can therefore be expected in case of large dissemination.

2.12 Lessons learned from the on-road trials in the ecoDriver project

The ecoDriver project is a collaborative project, in the sense that all partners have engaged together to share their collected data into a common database. The research questions list have been divided across partners, so that each partner is in charge of analysing one aspect, using data from all partners. It has been decided to use open source software (R software) for statistical computations. This improve the reliability of the approach by guaranteeing the consistent use of the same methods and algorithms. The adopted approach was different from that of previous FOTs for which each partner was in charge of analysing its own data collected during their trials. Although successful, this approach revealed other drawbacks that may require further attention for the upcoming projects. These are described in detail in Section 10 but can briefly be described as:

- Adopt a single experimental design for all experiments,
- ensure project partners accept to share the data required for the analysis,
- work in close collaboration between database managers and data scientists,
- agree on a Gantt chart for the whole data management chain and schedule a time margin for unpredictable delays,
- take care of the confidentiality of collected data into the data management process,
- use common open source tools and methodology, and share the code,
- automate the statistical analysis process, from code to formatted tables,
- do not underestimate the time needed for database computations,
- adopt a statistical methodology in line with the actual standards,
- plan theoretical and practical workshops about statistical methodology before starting to analyse data,
- scaling-up the results should be scheduled sequentially after the statistical analysis is done.

3 Description of systems and their behaviour

Nine different systems were tested in the real world trials that were conducted in SP3. Five systems were developed by OEMs (CRF, Daimler, BMW), one system by TomTom, an ecoDriver App by IFSTTAR and CTAG and the Full ecoDriver System (FeDS) by mainly CTAG and TNO. The systems differed in the information they used to provide an advice and/or feedback to the driver, the way the HMI operated and the events on which advice / feedback was provided. This chapter provides a coarse overview of these systems. For more detailed information (e.g., what was exactly shown in the HMI, how the systems exactly operated) the reader is referred to the underlying ecoDriver deliverables of SP1, SP2 and SP3 (e.g., 14.1, 33.1 and 33.3).

3.1 CRF system

CRF set up three prototypes hosted on an Alfa Romeo Giulietta (1.4 T-Jet 120CV*)*, Fiat Bravo 1.4 (Multi-air E5 Dynamic) and Lancia Musa (1.9 Multi-jet) to be used during SP3 on-real road trials. The three demonstrators, equipped with a CRF proprietary ecoDriver system, had different HMIs (see Figure 4):

1. The Fiat Bravo prototype had a visual HMI shown on the instrument cluster
2. The visual HMI of the Alfa Romeo Giulietta prototype was shown on the instrument cluster too, but with different layout and graphics and having haptic feedback too, provided to the driver by a counterforce throttle
3. The Lancia Musa had a visual HMI shown in a display in the central part of the dashboard.

(a) Fiat Bravo (b) Alfa Romeo Giulietta (c) Lancia Musa

Figure 4: CRF prototypes

The CRF systems did not use a map but used algorithms to learn the route and specific events. The events were the same for all three prototypes. During these events, drivers received eco-driving advice. These events were curves (see Figure 4a), roundabouts (Figure 4b), and traffic lights (Figure 4c). In general, if drivers on any part of the route drove faster than the ‘learned’ speed, advice was provided to slow down (indicated by an icon showing to release gas pedal). Green speed and gear shift indicator were also provided.

A ten-level average score was shown (shamrock in the Giulietta prototype, tree in the Musa prototype, leaf in the Bravo prototype) giving a global evaluation based on four indexes (acceleration, deceleration, gear and speed). All three HMIs gave post-trip information with the average score for deceleration, acceleration, gear and speed. The post-trip performance information (e.g. acceleration, deceleration…) was given by stars (from 1 to 5) — one star meaning bad performance, five stars meaning very good performance.

3.2 Daimler system

Daimler's ecoDriver prototype supports truck drivers to achieve a fuel-efficient driving style. A map-based electronic horizon is used to calculate a fuel-efficient strategy for manual driving mainly applicable on rural and city traffic. The system uses GPS and data from the vehicle's CAN bus including an estimated vehicle mass and the distance to the lead vehicle from a radar sensor.

The content of the additional ecoDriver screen in the vehicle is shown in Figure 5. Upcoming events along the route are shown in different parts of the display (this was on a separate display in the truck; so not integrated in the dashboard). Daimler provided information on the following events:

- approaching a lower speed limit
- approaching intersection or roundabout
- approaching a curve
- approaching hill's crest
- preceding vehicle detection
- exceeding a 'green' speed limit
- exceeding a legal speed limit
- crossing a lateral acceleration threshold
- information on upcoming hazards

Upcoming events with their distances are shown in the upper part of the display. Those can be either events that bring about a low target speed such as "left turn at an intersection" or events that are only shown to inform the driver like "lane ends, merge right" (see Figure 5 - Figure 7). In the left circle, a speedometer is shown. A small range above the legal speed limit is highlighted yellow (low penalties, tolerable for a short time) whereas the range above that is highlighted red (high penalties, to be strictly avoided). The recommended speed range is highlighted green. If there is a low target speed ahead (e.g. at an intersection), the target speed is marked with a red line (20 km/h in Figure 5).

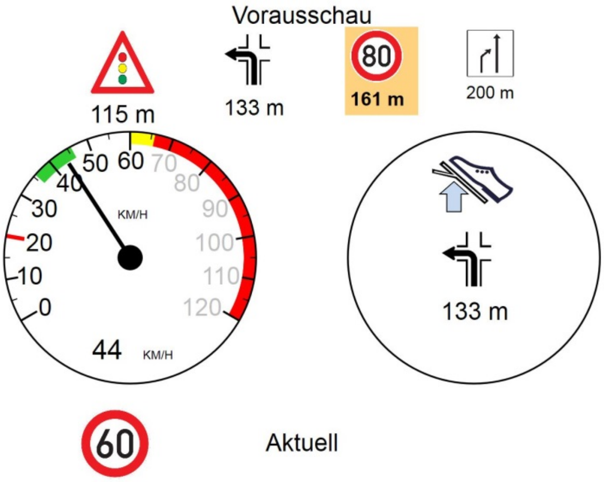


Figure 5: Coasting advice (right circle) shows the coasting advice icon (pedal and foot) and the reason for the advice: left turn at intersection in 133 m.

The right circle in the display shows variable information. If coasting advice is active, this advice and the reason for it are shown (Figure 5). In normal driving situations, the driver can choose between showing the distance to the lead vehicle (Figure 6), the optimal accelerator pedal position (Figure 7) and general status information.

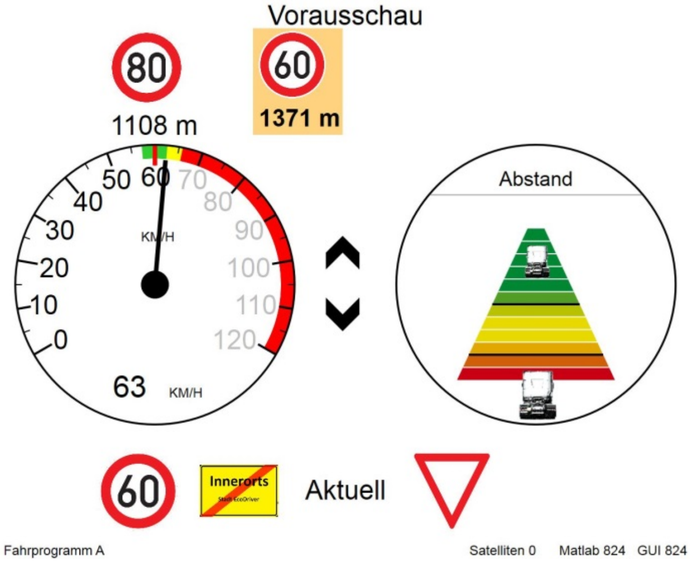


Figure 6: The distance to the lead vehicle can be shown in the right circle of the display. In the example shown, the lead vehicle is in the green zone, showing a safe distance. If the distance gets too low, coasting advice is shown.

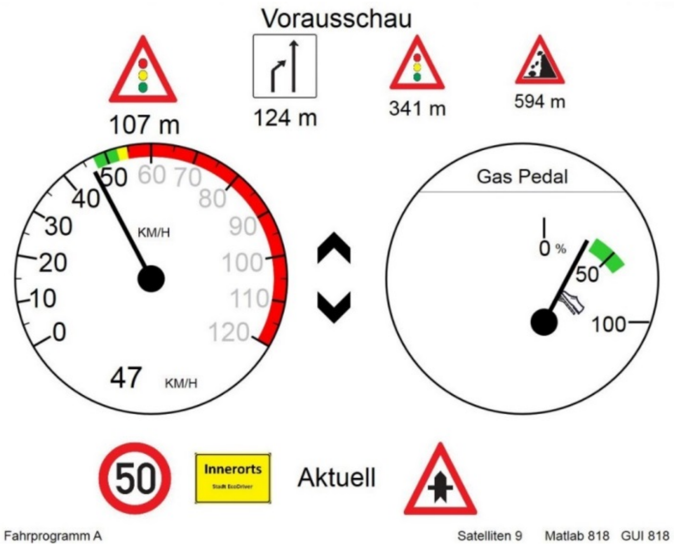


Figure 7: Upcoming road signs and their distances are shown on the upper part of the display. The signs depicted here are not necessarily a reason to reduce speed so they are just shown to inform the driver.

The lower part of the screen shows the current speed limit, an additional icon if the vehicle is within city limits and another icon if the vehicle has the right of way at the next intersection.

3.3 TomTom system

The TomTom aftermarket system shows feedback and advice to the driver to improve their eco-driving behaviour. Before and after the trip the driver can see his driving performance in graphs and statistics. The current system description focuses on the system while driving. The TomTom systems provides advice in the following scenarios:

- approaching an intersection, roundabout, motorway exit or lower speed limit (coasting advice; Figure 8)
- gear shift advice (Figure 9)
- green speed limit advice (Figure 10)
- crossing a deceleration or lateral acceleration threshold (e.g., harsh cornering; Figure 11)
- crossing an average fuel consumption threshold (Figure 12)
- crossing an idling time threshold (Figure 13)
- exceeding the legal speed limit (the speed bubble will turn amber or red).

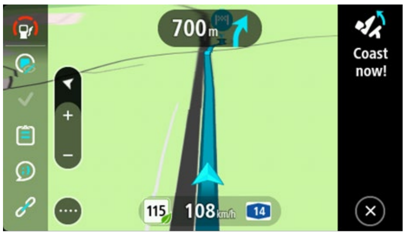


Figure 8: Coasting advice (TomTom)

Figure 9: Gear shift advice (TomTom)

Figure 10: Green speed advice in speed bubble

Figure 11: Example of harsh cornering alert

Figure 12: Fuel consumption indications

Figure 13: Idling alert

3.4 Leeds – TomTom system

The system tested on the hybrid bus fleet provided auditory only feedback based on a comparison between the fuel consumption of the current driver and that of the average driver. For the selected test route, the system monitored fuel consumption and then compared it with average fuel consumption across all drivers who had driven that vehicle along the test route previously. If the current driver used more fuel than the average they were presented with a single auditory alert tone (whose meaning had been defined to them previously). The purpose of the tone was to encourage the driver to consider how to be more fuel efficient on their next drive of the test route. The system was designed to provide feedback on eco-driving behaviour on a specific uphill, urban road section. Due to constraints imposed by the bus fleet operator, the system did not display any visual feedback regarding eco-driving performance.

3.5 BMW system

BMW has developed the ecoDriver system “ecoAssist” for forward looking eco-driving. The ecoAssist is connected to a digital map and in-vehicle communication with respect to the vehicle’s longitudinal dynamics (CAN-Bus) to achieve a reduction of fuel consumption and CO2 emissions. BMW’s ecoDriver

HMI assists and informs the driver via the dashboard and Head-up-display (HuD) on CO2 emissions and fuel consumption values. Connected to the HMI concept is the coasting mode (longitudinal dynamics). The vehicle switches automatically into the coasting mode when the driver does not use the throttle.

The colour of some of the gauges in the dashboard and the background colour in the HUD vary. For average or normal driving both colours are set to white. In case of high emissions the colours change to red indicating poor fuel efficiency. For economic drivers with high fuel efficiency and corresponding low emissions the dashboard and HUD colour changes to blue.

The different colour schemes are visualised in Figure 14 through Figure 16. Additionally, as can be seen in the dashboard display, the eco-driving performance was also indicated with stars where five filled blue stars (Figure 14) indicate highly efficient driving (low CO_2 values) and no filled stars poor performance (Figure 16). The bubbles reflect CO_2.

Figure 14: The BMW dashboard showing the white dashboard and HUD background colour (right; reflecting average eco-driving performance)

Figure 15: The blue dashboard and HUD background colour (right; reflecting good eco-driving performance)

Figure 16: The red dashboard and HUD background colour (right; reflecting poor eco-driving performance)

When the driver releases the throttle the vehicle automatically switches to a coasting mode indicated by a ‘sailing boat’ icon (Figure 17). The gear mode is then set to neutral. The coasting advice itself is provided in the HuD (Figure 18).

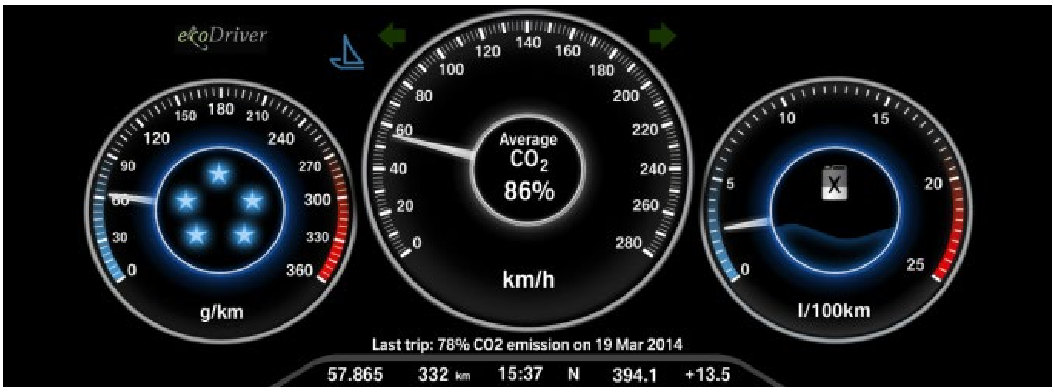


Figure 17: The coasting icon in the dashboard left of the speedometer

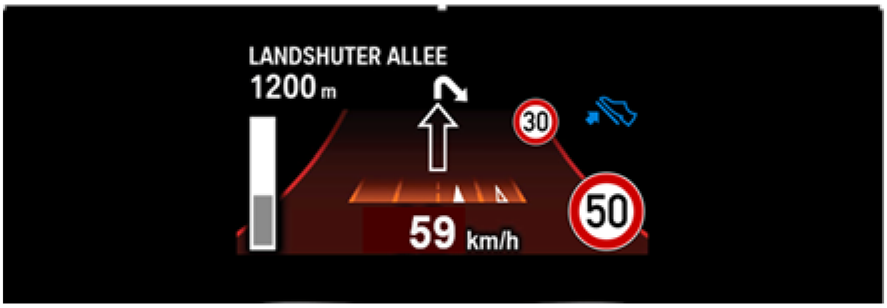


Figure 18: Coasting advice provided in the HuD (here for a lower speed limit).

Coasting advice is provided for the following events:

- approaching a lower speed limit
- approaching an alert sign that (may) requires to slow down (e.g. stop sign, yielding sign, sharp curve, roundabout, etc.)

3.6 Full ecoDriver System (FeDS; CTAG, TNO, IKA, VTI and Leeds)

The HMI of the Full ecoDriver System (FeDS) was mainly developed by CTAG and its behaviour was developed through interactions between CTAG, TNO, IKA, VTI, and Leeds. Since it was used in different vehicles the information to the driver was presented on a Samsung Galaxy Note II. The main screen of the FeDS is presented in Figure 19. The speedometer was shown with the current speed and the speed advice (in green), the current gear was indicated including gear shift advice, performance of the driver was indicated through green circles against a background of a tree indicating the eco-driving performance (five filled circles indicated excellent eco-driving performance and none a poor performance). The FeDS had the possibility to distinguish eco-driving performance at different levels (the level was indicated by a bronze, silver or gold coin on which your chosen 'avatar' was standing). However the feature of different levels was not used in the real world trials. The advised speed was shown continuously. It was considered that there would be low acceptance to advice that suggested driving well below a high speed limit. Therefore the decision was made that advised speed should be 100 km/h for speed limits over 100 km/h. Advice to reduce speed was provided for the following events:

- approaching an intersection
- approaching a lower speed limit
- approaching a curve

- approaching a preceding vehicle

The advised speed at these location was a “safe” speed, as opposed to the speed that would maximise energy savings, which would normally have been a continuation of the current vehicle speed. It was felt vital to prioritise safety over obtaining maximum energy savings/

After one of the events the driver received feedback on her/his performance. This was done by rating the performance using five stars where five highlighted stars indicate the best performance. As an example the advice and feedback for a curve are presented in Figure 20.

Figure 19: Main screen of FeDS

Figure 20: Advice to slow down for a curve (left) and the feedback on performance with a perfect score (right).

3.7 ecoDriver App (IFSTTAR, CTAG)

The ecoDriver App was developed by IFSTTAR and shares HMI features with the FeDS as described in the previous section. The ecoDriver App provides feedback analysis on acceleration, deceleration and gear shifting behaviour but it also displays feedforward information and advice about upcoming events (junctions, sharp curves, slopes, traffic lights, roundabouts, speed limits). The main difference from the FeDS is the sensor information used to provide advice and feedback to the driver. The main screen of the ecoDriver App is presented in Figure 21. Drivers could choose to show the performance tree or a map that was used for navigation. No speed advice was presented.

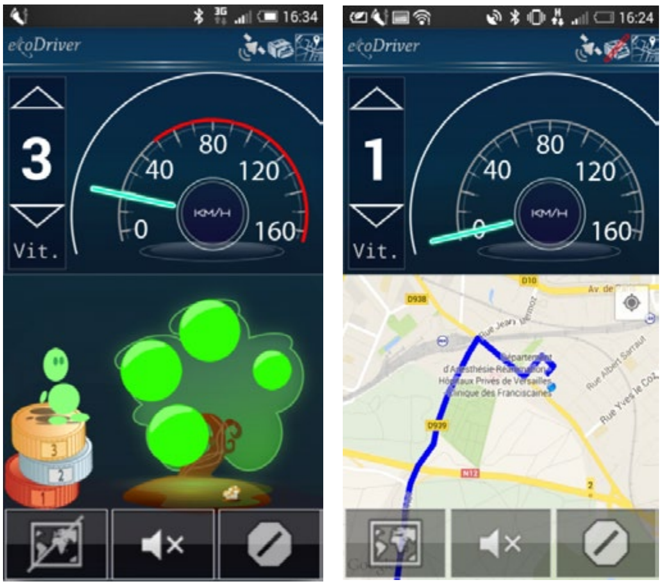


Figure 21: The main screen of the ecoDriver App with the performance tree (left) or with a map (right).

The ecoDriver App provided information, feedback and advice on the following events

- crossing an acceleration/deceleration threshold (Figure 22)
- on time or too late gear shift (Figure 23)
- approaching intersection
- going downhill
- approaching a curve (Figure 24)
- approaching a pedestrian crossing
- the posted speed limit

Figure 22: Feedback on harsh acceleration (left) and deceleration (right)

Late gear change !

Good gear change !

Figure 23: Feedback on gear shift performance

Figure 24: Example of advice to decelerate and the reason for deceleration (in this example a sharp curve)

3.8 Event-based system behaviour

Table 7 provides an overview of which systems were active at which events along the driven route, i.e. it shows the events where the system gives advice to the driver, thus potentially influencing driving behaviour when the system is active.

Each system being designed differently, the alerts were displayed differently across upcoming events or driving situation. For example, the Daimler system was designed for trucks and was able to advise the driver to stop accelerating when approaching a crest. This feature was unique to this system, but deserved a specific impact analysis. Therefore, it was necessary to identify and extract these situations from the collected data.

Table 6: System activity at events

System activity at events							
	BMW	**CRF**	**Daimler**	**TomTom**	**Leeds - TomTom**	**FeDS**	**Android**
Intersections	X	X	X	X		X	X
Sharp curves		X	X			X	X
Crests			X				
Speed limit going down	X	X	X	X		X	X
Uphill gradients					X		

4 Definitions

This chapter provides definitions, explanations and examples with respect to the concepts in the evaluation process. The evaluation approach is largely based on the FESTA Handbook (FESTA, 2014). Within the FESTA project, a list containing more than 140 Performance Indicators (PIs) was developed. The PIs were described according to a number of categories like “required measures”, “reliability”, “validity”, whether they mostly pertained to traffic safety, environmental issues, traffic efficiency or acceptance, etc. The FESTA approach was applied in the design of the ecoDriver evaluation studies. In ecoDriver Deliverable D41.1 (Kircher et al., 2012), the steps from Research Questions to Hypotheses, to Performance Indicators, Measures and Sensors have been detailed. The main concepts involved are presented below to facilitate a good understanding of the analysis in the following chapters.

4.1 Performance Indicators

A performance indicator (PI) is a quantitative or qualitative indicator, derived from one or several measures, agreed beforehand, expressed as a percentage, index, rate or other value, which is monitored at regular or irregular intervals and can be compared to one or more criteria.

- Hypotheses steer the selection of PIs and the criteria against which those should be compared. Hypotheses are seen as questions that can be answered with the help of measurable PI.
- Criteria can be baseline, different experimental conditions, absolute values, etc. This depends on the research questions and hypotheses.
- A denominator is necessary for a PI. A denominator makes a measure comparable (per time interval/per distance/in a certain location/…). Therefore “crash” or “near-crash” in themselves should rather be considered to be “events”, because they become comparable only when they get a denominator, like “number of crashes per year per 100.000 inhabitants”. For certain PIs either time or distance can be used in the denominator (e.g. number of overtaking manoeuvres, percentage of exceeding the posted speed limit).

PIs are in most cases not continuous but either aggregated in some way, or obtained at exactly one point. PIs related to speed could be, for example, the mean speed on a certain road segment, the standard deviation of speed on a road segment, the top speed or the minimum speed, or the point speed at a certain location. PIs can also be the number of crashes per year, or the percentage of time spent speeding.

4.2 Measures

A measure is the magnitude of a quantity such as length or mass relative to a unit of measurement, such as a meter or a kilogram.

Measures are the information logged from sensors, but measures often are not comparable in a meaningful way. Examples of measures are time and distance travelled, speed, outside temperature or vehicle weight. Measures are necessary to compute PIs. There are direct, indirect and self-reported measures. The events and Situational Variables (SVs) are special cases that are based on measures, and they will be discussed below.

4.2.1 Direct (raw) measures

A direct measure is logged directly from a sensor, without further manipulations except linear transformations.

Direct measures are logged directly from the sensor, which is the physical entity that delivers some output. In the case of an eye tracker a direct measure could be the gaze direction in x-, y- and z-direction, and in the case of a CAN bus a direct measure could be speed or steering wheel angle. If speed, however, is delivered in m/s, a linear transformation to km/h does not change the direct measure to a derived one. How the sensor arrives at its output does not influence whether a measure is direct or derived. Only manipulations done after having read the signal from the sensor are critical for the differentiation into direct and derived measures.

In many cases direct measures are logged continuously as long as a signal is present. If vehicle speed is logged via GPS, no signal might be present in tunnels, because the GPS device cannot receive a signal from the satellite in the tunnel. Here, no signal is obtained due to technical limitations. Radar that logs the distance to the car ahead will not provide a signal when there is no car ahead. Here the limitations are not of technical nature, but depend upon the situation. However, both speed and distance to the car ahead are considered to be continuous signals.

4.2.2 Derived (pre-processed) measures

A derived measure is a single measure calculated from a direct measure (e. g., by applying mathematical or statistical operations) or a combination of one or more direct (or derived) measures.

Derived measures are calculated from direct measures or other derived measures or a combination thereof. If a CAN bus and other sensors deliver both the own speed and the distance to the vehicle ahead, the speed of the vehicle ahead and the Time to Collision (TTC) can be derived from these direct measures. Both the speed of the vehicle ahead and the TTC would be considered derived measures, as the necessary computations are not only linear, but more complex transformations.

Derived measures are usually also continuous measures. They can be undefined, for example when TTC is computed in a car-following situation when the lead vehicle moves faster than the following vehicle. In principle, however, TTC is a continuous measure.

4.2.3 Self-reported measures

A self-reported measure is a subjective kind of data reported via questionnaires, interviews, focus groups, etc.

Self-reported measures are usually not obtained continuously, due to the very nature of the experimental setup. In most cases it is not even considered feasible to ask the drivers to fill in questionnaires or rating scales on a regular basis. Usually the drivers would fill in a battery of questionnaires before starting to drive a vehicle. They might answer some questions during the course of the study and finally they often fill out questionnaires at the end of the study. Then it is also possible to conduct interviews, either individually or as focus groups, or to resort to video confrontation techniques, where the driver is shown a particularly interesting event of his driving logs, on which he or she is asked to comment. Usually the results obtained through those data acquisition techniques are coupled to the log data.

4.2.4 External measures

A fourth type of measure, not present in the FESTA definitions, is used in ecoDriver, as it simplifies the classification of the measures to record.

An external measure is provided by data sources outside of the log equipment used in the study.

Examples for those data sources could be crash databases, weather databases, map data, and road databases. In many cases the data obtained by the log equipment within the study are related to the data from the external databases via for example GPS position and time.

4.3 Descriptive variables

On overview of the descriptive variables is provided in Table 7 and described in more detail below.

Table 7: Overview of descriptive variables

Item	Definition
Situational variables	A situational variable (SV) indicates a fixed situation with respect to time and position. It is a categorical variable with two or more values.
Segments	Such variables are used to identify some situations (driving conditions, specific manoeuvers, etc.) that could vary with time and position. It is also used to identify sections of data that may need to be extracted for analysis afterwards. For example, segments can be derived from SV's related to an infrastructure element to represent its influence on driving. It is a categorical variable with two or more values.
Events	Such variables refers to a more complex driving event, usually related to driver behaviour. In the ecoDriver project, events have been defined related to infrastructure elements like zebra crossings and to specific driving situations like accelerating after standstill. It is a binary variable which value is equal to 1 when the corresponding event is detected in some way. The value equals 0 if the event is not present.

4.3.1 Situational variables

A Situational Variable (SV) is an aspect of the surroundings made up of distinguishable levels. At any point in time at least one of these levels must be valid.

SVs describe the surroundings in which the drivers find themselves. Each SV has several levels, of which at least one is valid at each point in time. Wherever one is driving, there is always at least one road type, be it rural, urban, motorway, or even terrain driving. Similarly, there is always some kind of weather (sunny, dry, rain, snow, etc.).

For data analysis it can be of interest to be informed about certain aspects of the current situation, for example because only these aspects are of interest for analysis, or because certain aspects may confound the results. It is possible, for example, that the eco driving performance varies across infrastructure types, and should be evaluated separately for each type.

Then it is important to be able to select those portions of the data stream where road types are different. It might also be possible that the outside temperature is a confounding factor, for example when fuel consumption is under investigation. In that case it is necessary to be informed about the SV "outside temperature" in order to be able to either compare data that come from trips with the same outside temperature, or to account for the effects produced by variations in outside temperature. It may be the case that not only one but several SVs are required to be at a certain level at the same time.

Thus a situation is one specific level or a combination of more specific levels of situational variables. A situation could be any of the following:

- A driver in a car-following situation.
- A driver in a car-following situation on the motorway.
- A driver in a car-following situation on the motorway in daylight.
- A driver in a car-following situation on the motorway in daylight with one passenger.
- ...

Each situation in the list above becomes more specific, that is, it is less and less likely to find the specific situation in the data material, but on the other hand the variation between the different instances of this situation is likely to be smaller. For some very specific hypotheses it may be necessary to look for very specific situations, while for other broader hypotheses more general situations might be enough.

4.3.2 Events

An event is something that happens in a specific period of time which is individuated combining (pre-processed) measures according to predefined rules.
A sub-event is a specific sub-set of an event.

Events are specific occurrences during driving that occur if certain preconditions are fulfilled for at least one measure. Speeding, for example, is an event, because it occurs when the speed signal exceeds the speed limit. Further examples of events are overtaking manoeuvres, car following, turning and hard braking, but also incidents, near-crashes and crashes. Related to infrastructure elements, sub-events can be the approach to, the actual passing of, and driving away from e.g. an intersection.

Events can be dangerous, but do not have to be. Events in themselves can be counted, or otherwise aggregated, to make them a basis for PIs. The number of crashes is a well-known PI, but it is also possible to count the number of overtaking manoeuvres or the number of hard braking manoeuvres. It is also possible to use other event related measures as PI – for example the average duration of an overtaking manoeuvre. Finally, PIs can be computed within the occurrence of an event. The mean or the maximum speed within an overtaking manoeuvre or the number of glances to the rear-view mirror during car following might be of interest.

The relationship between situational variables and events is shown in Figure 25.

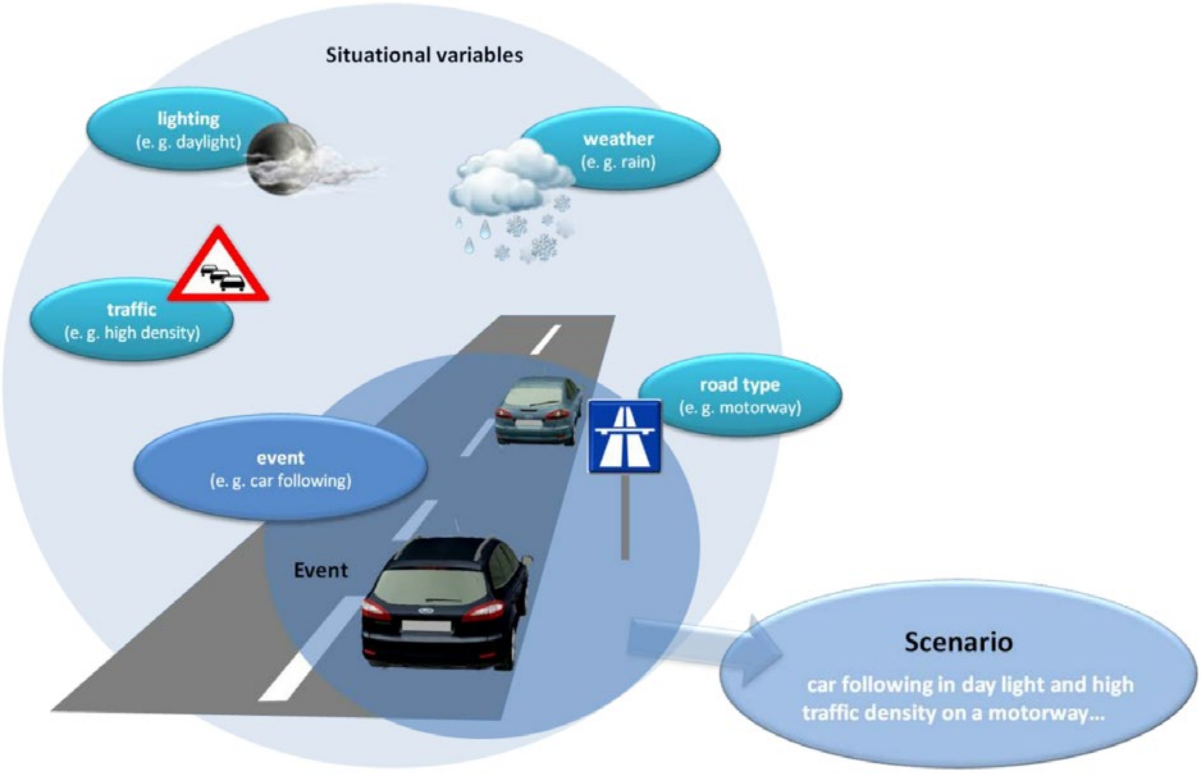


Figure 25: Link between situational variables and events, extracted from a Fot-Net Data presentation from A. Zlocki and S. Koskinen (2016).

4.4 Summary list of Performance Indicators

In Table 8 below, the complete list of PIs computed within the ecoDriver project is given, together with a short definition of each. The detailed definitions can be found in deliverable D41.1 (D41_1 Performance indicators and ecoDriver test design). The PIs linked to a specific research question are described in annexes E to G.

Table 8: Summary list of PI used for the ecoDriver analyses

PI name	**Definition**
Megajoules_per100km	Megajoules per 100km
Litres_fuel_per100km	litres per 100 km
Grams_CO2_per100km	petrol: litres per 100 km * 2370 diesel: litres per 100 km * 2650
Litres_fuel_per100km_model	Model based estimation
Grams_CO2_per100km_model	Model based estimation
Avg_rpm_shift_up	average rpms when shifting up
Index_gear_rpm	Index_Gear_RPM (average rpm by gear when driving, weighted by the time with gear engaged)
Positive_kinetic_energy	$PKE = \frac{\sum(v_f^2 - v_i^2)}{x}$ when $\frac{dv}{dt} > 0$ where: vf = final speed (m/s) vi= initial speed (m/s) Condition vf>vi x= total distance driven (m)
Avg_speed	average speed of a segment (km/h)
Avg_speed_distance_based	total distance travelled divided by the total time
Stddv_based	standard deviation of speed over the segment (km/h)
Avg_time_headway	average TimeHeadway (s)
Time_engine_brake_ratio	% of time of driving with engine brake. The engine brake condition is characterized by the following conditions: non zero speed, no neutral, no pressure on the brake pedal and the accelerator pedal. Or alternatively by: negative engine couple,
Max_acc	the maximum acceleration during the segment (m/s2)
Avg_slope	Average slope (%)
Percentil_slope_95	95 percentile of slope (%)
Percentil_slope_5	5th percentile of slope (%)
Range_slope	Range of variation of the slope (95th percentile - 5th percentile) (%)
Avg_pos_acc	Average of positive acceleration (m/s^2)
Avg_neg_acc	Average of negative acceleration (m/s^2)

PI name	Definition
Avg_pos_acc_06	Average positive acceleration above 0,6 m/s²
Avg_neg_acc_06	Average negative acceleration below -0.06m/s²
Percentil_pos_acc_95	95percentile of positive acceleration (m/s²)
Percentil_neg_acc_5	95percentile of negative acceleration (m/s²)
Stddv_acc	Standard deviation of acceleration (m/s²)
Acc_above_05_ratio	% of time acceleration above 0.5 m/s² (only when Stationary>0)
Acc_above_1_ratio	% of time acceleration above 1 m/s² (only when Stationary>0)
Acc_above_2_ratio	% of time acceleration above 2 m/s² (only when Stationary>0)
Acc_above_3_ratio	% of time acceleration above 3 m/s² (only when Stationary>0)
distance	Distance travelled by the vehicle within the section (meters)
duration	Time spent within the section (in seconds)
Slope1_time_ratio	Percentage of time with Slope=1
Slope2_time_ratio	Percentage of time with Slope=2
Slope3_time_ratio	Percentage of time with Slope=3
Slope1_distance_ratio	Percentage of distance with Slope=1
Slope2_distance_ratio	Percentage of distance with Slope=2
Slope3_distance_ration	Percentage of distance with Slope=3
Roadtype1_time_ratio	Percentage of time with Roadtype=1
Roadtype2_time_ratio	Percentage of time with Roadtype=2
Roadtype3_time_ratio	Percentage of time with Roadtype=3
Roadtype4_time_ratio	Percentage of time with Roadtype=4
Roadtype1_distance_ratio	Percentage of distance with Roadtype=1
Roadtype2_distance_ratio	Percentage of distance with Roadtype=2
Roadtype3_distance_ratio	Percentage of distance with Roadtype=3
Roadtype4_distance_ratio	Percentage of distance with Roadtype=4
Sl20_time_ratio	Percentage of time with Speed limit=20
Sl30_time_ratio	Percentage of time with Speed limit=30
Sl40_time_ratio	Percentage of time with Speed limit=40
Sl50_time_ratio	Percentage of time with Speed limit=50
Sl60_time_ratio	Percentage of time with Speed limit=60
Sl70_time_ratio	Percentage of time with Speed limit=70
Sl80_time_ratio	Percentage of time with Speed limit=80

PI name	Definition
Sl90_time_ratio	Percentage of time with Speed limit=90
Sl100_time_ratio	Percentage of time with Speed limit=100
Sl110_time_ratio	Percentage of time with Speed limit=110
Sl120_time_ratio	Percentage of time with Speed limit=120
Sl130_time_ratio	Percentage of time with Speed limit=130
Sl20_distance_ratio	Percentage of distance with Speed limit=20
Sl30_distance_ratio	Percentage of distance with Speed limit=30
Sl40_distance_ratio	Percentage of distance with Speed limit=40
Sl50_distance_ratio	Percentage of distance with Speed limit=50
Sl60_distance_ratio	Percentage of distance with Speed limit=60
Sl70_distance_ratio	Percentage of distance with Speed limit=70
Sl80_distance_ratio	Percentage of distance with Speed limit=80
Sl90_distance_ratio	Percentage of distance with Speed limit=90
Sl100_distance_ratio	Percentage of distance with Speed limit=100
Sl110_distance_ratio	Percentage of distance with Speed limit=110
Sl120_distance_ratio	Percentage of distance with Speed limit=120
Sl130_distance_ratio	Percentage of distance with Speed limit=130
Freedriving1_time_ratio	Percentage of time with Freedriving=1
Cruising1_time_ratio	Percentage of time with Cruising=1
Stationary0_time_ratio	Percentage of time with Stationary=0
Stationary1_time_ratio	Percentage of time with Stationary=1
Stationary2_time_ratio	Percentage of time with Stationary=2
Sharpcurve1_time_ratio	Percentage of time with Sharpcurve=1
Sharpcurveentry1_time_ratio	Percentage of time with Sharcurveentry=1
Sharpcurveexit1_time_ratio	Percentage of time with Sharpcurveexit=2
Trafficlight1_time_ratio	Percentage of time with Trafficlight=1
Trafficlight3_time_ratio	Percentage of time with Trafficlight=3
Speedbump1_time_ratio	Percentage of time with Speedbump=1
Speedbump3_time_ratio	Percentage of time with Speedbump=2
Zebra1_time_ratio	Percentage of time with Zebra=1
Zebra3_time_ratio	Percentage of time with Zebra=3
Intersection1_time_ratio	Percentage of time with Intersection=1

PI name	**Definition**
Intersection3_time_ratio	Percentage of time with Intersection=3
Crest1_time_ratio	Percentage of time with Crest=1
Overspeeding1_time_ratio	Percentage of time with Overspeeding=1
Speed_limit_start	Speed limit at the start of the segment
Speed_limit_end	Speed limit at the end of the segment
Avg_speed_cruising	Average speed when cruising
Avg_speed_freedriving	Average speed when free driving
Median_time_headway	Median time headway

Other elements to be considered in the analyses are provided in Table 9.

Table 9: Additional PIs considered in the analysis

PI name	**Definition**
acceleration distribution	histogram acceleration
deceleration distribution	histogram deceleration
speed profile	speed over time for the analysis segment
time headway distribution	histogram of time headway over the analysis segment
rear time headway distribution	histogram of rear time headway over the analysis segment

5 Analysis methods

This chapter summarises the main choices of the ecoDriver research team in order to produce relevant and sound results for such complex data. The complete and final list of research questions is provided, together with detailed explanations of the practical steps of the analysis technique. The main choices are discussed, and relevant datasets are described.

5.1 Hypotheses tested

The hypotheses investigated are listed in Table 10. The hypotheses were developed at an early stage in the project and modified as the project progressed. Some were merged, some have been rephrased, and some others passed to another work package because they were impossible to test with experimental data (for example, the evaluation of the decrease of energy use according to the penetration rate was transferred to SP5).

Table 10: Summary of the hypotheses studied in this deliverable

Main section in deliverable	**Research Question category**	**Hypothesis number**	**Hypothesis**
Energy & emissions	ENERGY	1	Using an ecoDriver system will reduce the average fuel consumption and CO_2 emissions
		2	Using an ecoDriver system will reduce the average energy consumption
		3	Using an ecoDriver system will reduce the average NOx emissions
Driver workload and attention	WORKLOAD	4	Using an ecoDriver system will increase driver workload
		5	Workload varies across the different ecoDriver system types
	ATTENTION	6	Using an ecoDriver system (which provides in-trip feedback), drivers are more distracted
		7	In-car feedback from the ecoDriver system causes inappropriate/dangerous visual behaviour, in terms of glances towards the device
		8	Using an ecoDriver system, the driver will look more at the speedometer/rev counter
Driver behaviour	SPEED	9	Using an ecoDriver system the average velocity when cruising will be lower
		10	Using an ecoDriver system the average free velocity will be lower

Main section in deliverable	Research Question category	Hypothesis number	Hypothesis
	SPEED SITUATIONS		Using an ecoDriver system, speed will change when driving before/at locations where a low speed is recommended by the system, such as:
		11	Location: Intersections
		12	Location: Zebra crossings
		13	Location: Speed bumps
		14	Location: Sharp curves
		15	Location: Crest
		16	Location: Speed limit changes
	THW DISTANCE SITUATIONS	17	Using an ecoDriver system, the time headway distribution to leading vehicle will change
			Using an ecoDriver system, there will be shorter distances to vehicles before/at safety critical locations, such as:
		18	Location: Intersections
		19	Location: Zebra crossings
		20	Location: Speed bumps
		21	Location: Sharp curves
		22	Location: Crest
		23	Location: Speed limit changes
	EVENTS	24	Using an ecoDriver system, there will be more red or amber light violations
		25	Using an ecoDriver system, there will be less overtaking manoeuvres
		26	Using an ecoDriver system, there will be less speeding
	4 GOLDEN RULES	27	Using an ecoDriver system, the average rpm when shifting up will be reduced
		28	Using an ecoDriver system, the weighted average engine rpm will be decreased
		29	Using an ecoDriver system, the variability of speed profiles will be decreased
		30	Using an ecoDriver system, the use of the engine brake will be improved
	ACCEL/DECEL	31	Using an ecoDriver system, the acceleration distribution will change

Main section in deliverable	Research Question category	Hypothesis number	Hypothesis
		32	Using an ecoDriver system, the deceleration distribution will change
		33	Using an ecoDriver system, acceleration after being stationary will be less aggressive
	ACCEL/DECEL SITUATIONS		Using an ecoDriver system, the acceleration distribution will change before/at the following locations:
		34	Location: Intersections
		35	Location: Zebra crossings
		36	Location: Speed bumps
		37	Location: Sharp curves
		38	Location: Crest
		39	Location: Speed limit changes

5.2 Hypotheses analysis methodology

The overall aim of the analysis is to address almost 40 well-defined hypotheses. Although many statistical analysis methods may exist to answer such questions, from the simplest to far more complex ones, a common scheme has emerged from previous experiences. Indeed, taking full advantage of the richness of the data at its finest level (multiple 10 Hz sampled signals) is often a very difficult task. Practitioners rely instead on data reduction methods first, followed by more or less complex linear analysis (Anova, GLMM, etc.).

Most of the hypotheses are linked to a significant difference for one or more PI, between baseline and treatment.

- **Example:**
  - Using an ecoDriver system, the average velocity, when cruising, will be lower

According to statistical standards, such decisions can be achieved through the usage of statistical tests theory. This framework allows controlling errors when a decision is made using statistical tests. The goal of this theory is to search for a significant difference among one or more PIs, between two or more conditions.

This general type of analysis is sometimes called **Aggregation based analysis (ABA).** This is a type of analysis for defining changes between baseline and treatment in terms of how driving performance changes over a range of traffic situations. Examples include the predicted increase in average following distance, and general decreases in travel speed when equipped with the ecoDriver system. The basic principle for ABA is to identify changes that occur when the evaluated system is being used in driver performance measures that are aggregated over longer time segments, such as average time headway or mean travel speed, and then interpret this change in terms of driving behaviour improvements or decrements. Again, the selection of measures has to reflect ideas about underlying driving behaviour, and in what way a change in the aggregate performance measure is predictive of a change in actual driving behaviour.

ABA analysis applies primarily to systems which are intended to change certain driver performance measures over time, such as how much fuel is consumed, lead vehicle following distances and average travel speeds. As the ecoDriver systems should impact driving behaviour on various dimensions, a large number of performance indicators are used to study the impacts on travel efficiency, road safety, fuel consumption, and many other aspects. The process will be as shown in Figure 26.

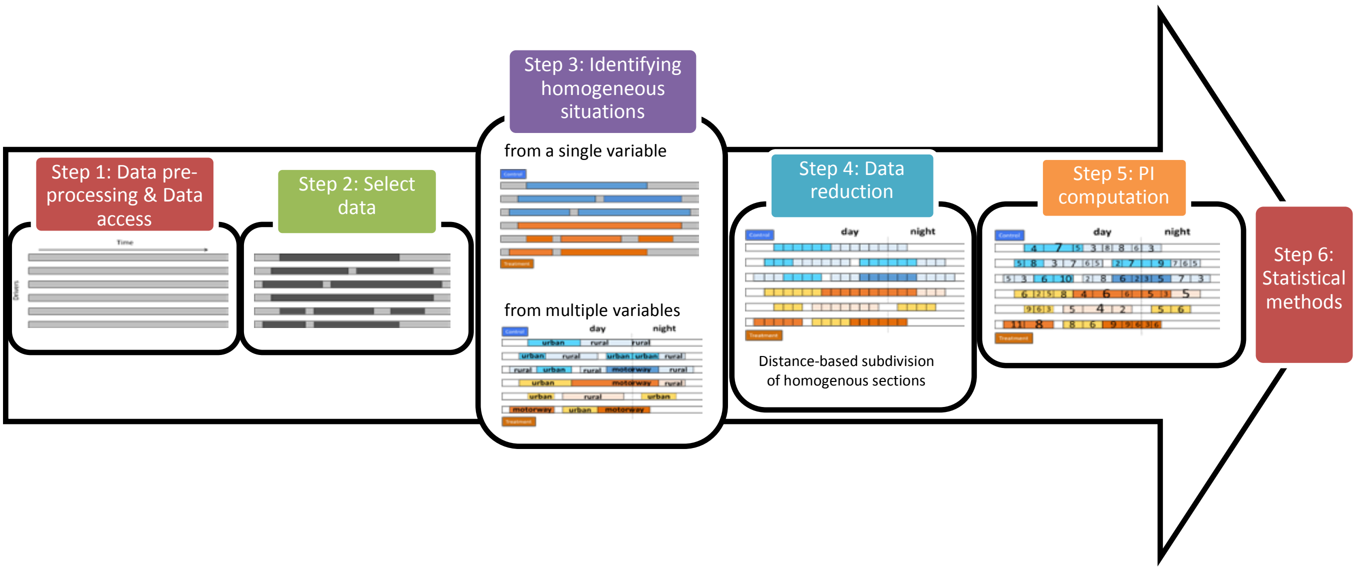


Figure 26: Overview of the data treatment and analysis process for a classical research hypothesis

5.2.1 Step 1: Data pre-processing and data access

The first step of the data analysis process consists of accessing the data. The main assumption here is that a full quality check and pre-processing step has been carried out by partners in charge of the common database. Necessary pre-treatments consist of the following steps:

- Quality check and filtering
- Enrichment and second quality check
- Computing derived measures.

Data are then available in the form of 10Hz sampled data for several variables, and those data are organised by trips, Figure 27.

Figure 27: Illustration of 6 different trips, sorted by time, available for data treatment and extraction.

Hypothesis example:

Compared to baseline, average velocity, when cruising, will be lower when using an ecoDriver system.

Step 1:

It consists of computing the additional segment variable “cruising” that identifies portions of data where the driver is driving at a stabilised speed.

5.2.2 Step 2: Select data

Once accessed, the suitable subsets of data are identified. Unacceptable quality or absence of a specific sensor (radar for example) are examples of justifications to use only parts of the full data set, Figure 28.

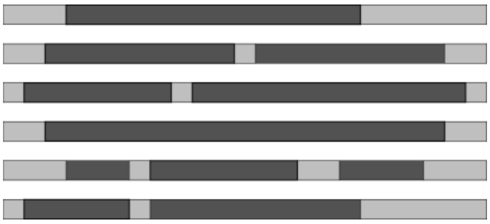


Figure 28: Illustration for the data selection step.

Hypothesis example:

Compared to baseline, average velocity, when cruising, will be lower when using an ecoDriver system.

Step 2:

It consists of selecting the data where the segment variable “cruising” is available and with value one (value zero being a non-cruising driving situation). Speed needs also to be available for Step 5 (PI computation).

5.2.3 Step 3: Identifying homogeneous situations

Having identified the necessary data to address a specific hypothesis, it is important to characterise the main factors that will be analysed for the hypothesis. Here, all the main factors are assumed to be categorical variables. In order to ensure homogeneity for these factors, the data needs to be sub-divided into homogeneous portions. This consists of identifying portions of data with a unique value for each factor, or for a combination of them.

5.2.3.1 From a single variable

When the hypothesis is simple, as when comparing a simple PI between baseline and treatment, a single categorical variable (sometimes binary) can be used to ensure homogeneity. Harmonisation using a single categorical variable is well suited for performing an analysis of variance (ANOVA) for a single factor afterwards. This is illustrated in Figure 29.

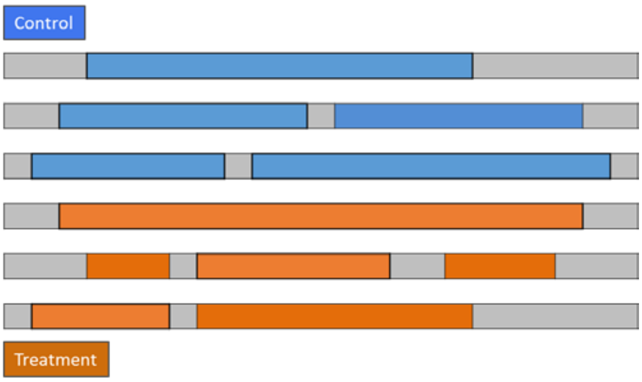


Figure 29: Illustration of the simplest form of homogenisation process.

Hypothesis example:

Compared to baseline, average velocity, when cruising, will be lower when using an ecoDriver system.

Step 3:

It consists of identifying only baseline and treatment phases within the cruising situations. In that case, this value cannot change during the trips.

5.2.3.2 From multiple variables

The hypotheses usually refer to several factors whose effects are to be studied in a single analysis. It is particularly useful when the effect is impacted by external conditions such road type, traffic level, etc. This is illustrated in the following figures.

- In Figure 30, the variable “baseline/experiment” is combined with “daylight” to identify four different conditions to be compared in the data.
- In Figure 31, the variable “baseline/experiment” is combined with "daylight" and with "road-type" variables to identify homogeneous subsets in the data (urban-day, rural-day, motorway-day, urban-night, rural-night, and motorway-night, each of them for both treatment and baseline).

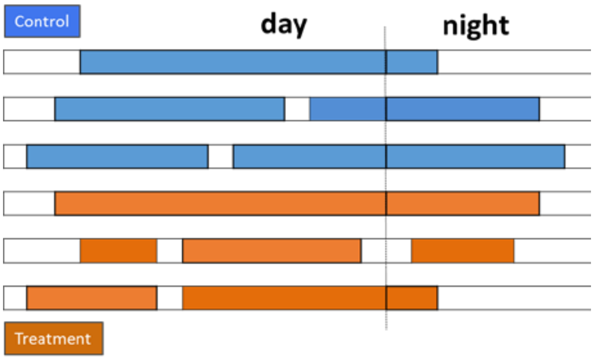


Figure 30: Illustration of the homogenisation process for multiple variables: combining “baseline/experiment” with “daylight”.

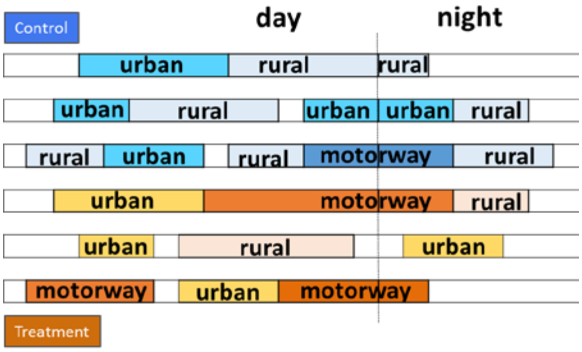


Figure 31: Illustration of the homogenisation process for multiple variables: combining variable “baseline/experiment” with "daylight" and "road type".

Hypothesis example:

Compared to baseline, average velocity, when cruising, will be lower when using an ecoDriver system.

Step 3:

Let’s assume that the difference between baseline and treatment can be different across different road types. This implies road-type is a main factor, to be combined with baseline/treatment and the cruising situation during analysis. This step allows identification of the following conditions in the data: Baseline*urban, baseline*rural, baseline*motorway, treatment*urban, treatment*rural, treatment*motorway.

5.2.4 Step 4: Data reduction

A classical research hypothesis looks for differences in one (or more) performance indicator across various conditions. Subsets of data identified at previous steps (step 1 to step 3) should therefore be transformed into aggregated values that will further be used to fit statistical models. However, PIs are often harmonised using a time basis (km/h, m/s, etc.) or a distance basis (numbers of events per km, number of stops per km, etc.), and therefore need to be computed for comparable situations. For example, the average speed over 20 minutes has much less variability than the average over one minute. As the situations identified previously are non-homogeneous both in time and distance, there is a need for a further step called “data reduction”. This step consists of subdividing the situations into smaller portions of identical sizes.

This method is recommended when the targeted behaviour is likely to change frequently across the trip. For example, longitudinal dynamic (speed profile) is impacted by the infrastructure and therefore can change many times during a trip. Computing speed-related PIs over a long section leads to values with low variability, merging a range of different infrastructure types.

This method is based on sub-setting the data into smaller portions of identical distance or duration. Each homogeneous section identified at the previous step is split into smaller portions, whose maximum duration or distance is controlled by a single parameter (see Figure 32). All the shorter subsets below the chosen distance or duration are excluded from the analysis.

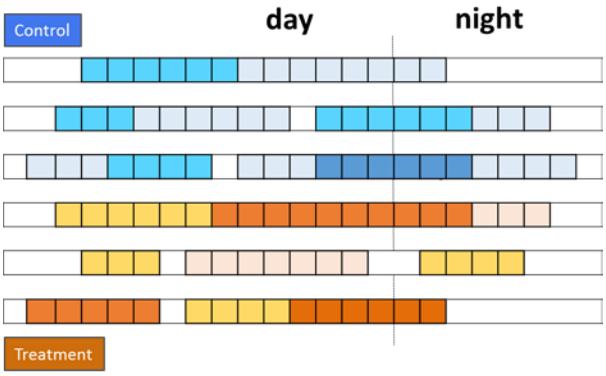


Figure 32: Illustration of the time-based subdivision of data.

Hypothesis example:

Compared to baseline, average velocity, when cruising, will be lower when using an ecoDriver system.

Step 4: Method 2

Let's assume road-Type And baseline/treatment were used in the homogenisation step.

Each similar condition is divided into 30 seconds portions of data before PI computation. Each trip is then reduced into a maximum of (Trip-duration / 30 seconds) different aggregated values.

→ no need to weight data with distance for analysis

→ Still need to weight data with duration for analysis (if needed)

Within the ecoDriver project and after careful analysis of the implications on the methodology, it has been decided to subset the driving data according to distance. The main reason is due to the physical aspects of eco-driving: many recommended eco-driving actions are required based on the presence of an infrastructure element (stop sign, road slope, zebras, etc.). Systems tested were also designed to alert the driver based on map information. It is therefore logical to base our comparisons on situations homogeneous in distance.

5.2.5 Step 5: PI computation

Once the trips are divided into smaller homogeneous subsets, aggregated performance indicators are computed, Figure 33. Each subset is represented by a line in the final table, the columns being the computed indicators and the meta-variables. The table is then ready for using main statistical methods based on linear models (ANOVA, GLM, GLMM, etc.).

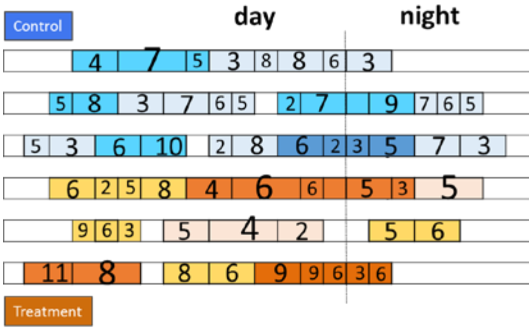


Figure 33: Illustration of the PI computation step. The different sizes of the numbers represent their respective weights in the final data set.

5.2.6 Step 6: Statistical analysis

In terms of the methodology, a drawback of contingency tables is that it is only possible to consider one factor at a time, and interaction/confounding effects cannot be addressed. Furthermore, contingency tables assume that observations are independent of each other, an assumption which does not suit FOT data very well, as it will contain unavoidable driver-specific correlations (i.e. some drivers will experience more events than others).

To study interacting/confounding factors and to account for these driver specific correlations, more sophisticated statistical models need to be applied. These models are generalisations of the linear models which have been adapted to a binary outcome, something which suits the ABA analysis division of events into baseline and treatment events well. These models include additional parameters to deal with correlations, and confounding factors are regarded as explicative variables that can be used to predict event probability.

One such model is the “Generalised Estimated Equations” (GEE) model, originally developed to model longitudinal data by Liang and Zeger (1986), which assumes that observations are marginally correlated. Another such model is “Generalised Linear Mixed Models” (GLMM). Similar to the GEE model, GLMM assumes correlated observations for the same driver. In addition, GLMM also assumes that there is a random effect associated with each individual driver (i.e. one driver can be associated with higher and another with lower risk of event involvement). This has the additional advantage of allowing to control for a small population of drivers being involved in a large proportion of safety events, something which indeed may become an issue (Dingus et al., 2006). Both GEE and GLMM models can also accommodate multiple risk factors, which allow those factors to be evaluated simultaneously. Indeed, this capability may also be used to evaluate different systems in use at the same time or at different times but with possible interactions. For the final dataset, these models were applied where appropriate, depending on the system tested and the events analysed. For a more technical and detailed description, see Liang and Zeger (1986) and Guo and Hankey (2009) for a focus on naturalistic driving data.

Statistical analyses were conducted using R, which is a free software environment for statistical computing and graphics (R Core Team, 2015; Hornik, 2015). A p-level of 0.05 was used to distinguish statistically significant effects.

5.2.7 Practical considerations for data preparation

Most statistical models require some theoretical assumptions to be met by the data. The most common one is the Gaussian distribution of the studied values. For the ecoDriver research hypotheses, most PIs follow Gaussian distributions, or at least with a sufficiently small deviation to avoid false results. Despite this positive picture, some specific PIs do not follow a Gaussian distribution at all and require a specific treatment. This is the case, for example, when dealing with percentage- based PIs, which tend to have two peaks, one near 0, and one near 100.

To deal with such cases, it is necessary to transform the PI using a monotonic increasing function, which keeps the direction and significance of the observed changes in the PI's values. As an example of this situation, we detail below the case of hypotheses 34-39 which is dealing with acceleration changes based on the 95th percentile of negative acceleration.

In the data exploration it was discovered that the 95th percentile of negative acceleration (percentil_neg_acc_5) is the most representative performance indicator on how harsh is the deceleration process for slowing down before an event. An example empirical cumulative density function over all event-based measurements before a sharp curve for the baseline and ecoDriver system is shown in Figure 34.

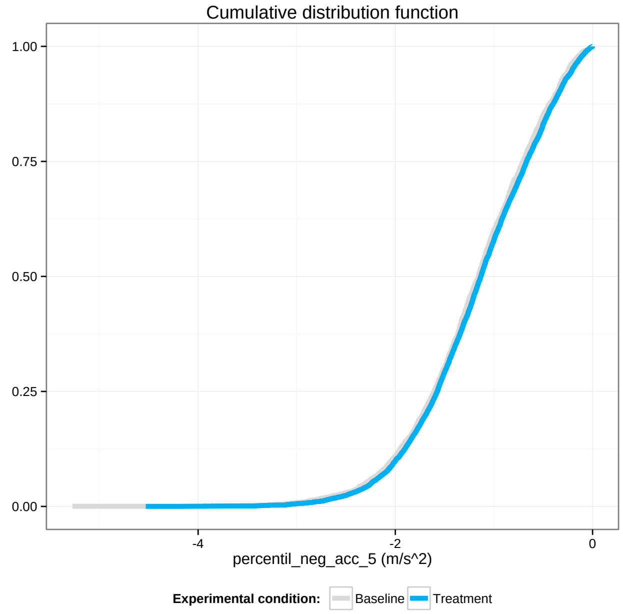


Figure 34: Empirical cumulative density function of percentil_neg_acc_5 for experimental phase and baseline.

The generalised linear mixed model, which is intended to use for the statistical evaluation, however demands that the data are normally distributed. According to Figure 34 and the definition of the "negative acceleration" this is not possible as the values cannot be positive and are heavily skewed. Therefore, the data were first transformed with the square root function to have more normally distributed data, such that the mixed linear model becomes a valid evaluation tool. Because the negative acceleration values are in the negative half space, first a change of sign is performed, such that the square root is applicable to the data values. The resulting empirical cumulative density function of the transformed 95th percentile of the negative acceleration (sqrt_percentil_neg_acc_5) is shown in Figure 35. The same transformed PI is also used for all other evaluations of Hypotheses 34-39. The same kind of procedure has also been applied for Hypotheses 29 and 30.

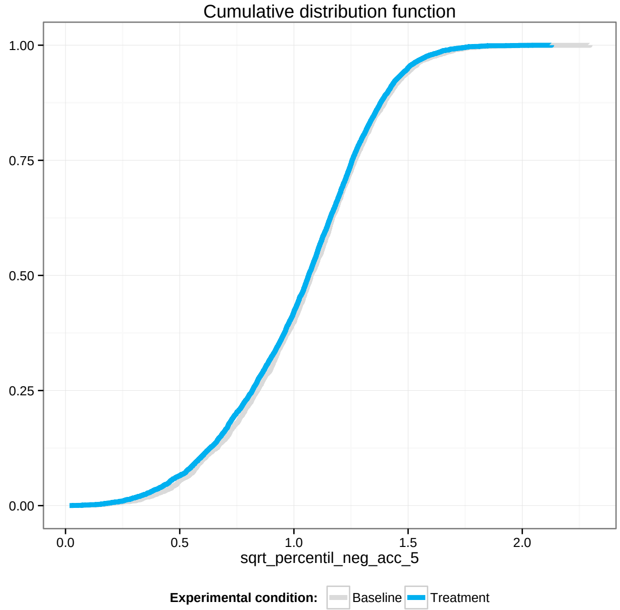


Figure 35: Empirical cumulative density function of the transformed sqrt_percentil_neg_acc_5 for experimental phase and baseline.

5.2.8 Cumulative distribution vs. model results

Intuitively, one expects to see the effect of the ecoDriver system in the cumulative distribution of performance indicators. Figure 36 shows the cumulative distribution of the transformed deceleration values before sharp curves on urban roads for the non-haptic and the haptic ecoDriver system. The distribution function is shifted to the right, i.e. towards higher values, with the haptic system. This is the opposite of what was expected. The haptic system should have a greater effect than the non-haptic system and result in lower deceleration values. In contrast, the model-based approach results in a significant reduction of the estimated deceleration values on urban roads as expected (Table 11).

The unexpected behaviour of the cumulative distribution is due to an unbalanced number of observations for cars and trucks as shown in Table 12. The deceleration values of cars are generally higher than for trucks. For the non-haptic system, there is a similar number of observations for cars and trucks. For the haptic system, there are many more observations for cars than for trucks, making the average deceleration value higher and shifting the cumulative distribution function as shown. Nevertheless, deceleration values are lower both for cars and for trucks with the haptic system compared to the non-haptic system. This is taken into account by the statistical model, making an adequate estimate of the deceleration values and the effect that the haptic system has. This example shows why the chosen statistical models are suited to do these analyses. Cumulative distributions can be easily influenced by unbalanced numbers of observations, giving confusing results. For that reason, cumulative distributions are not shown in the individual analyses.

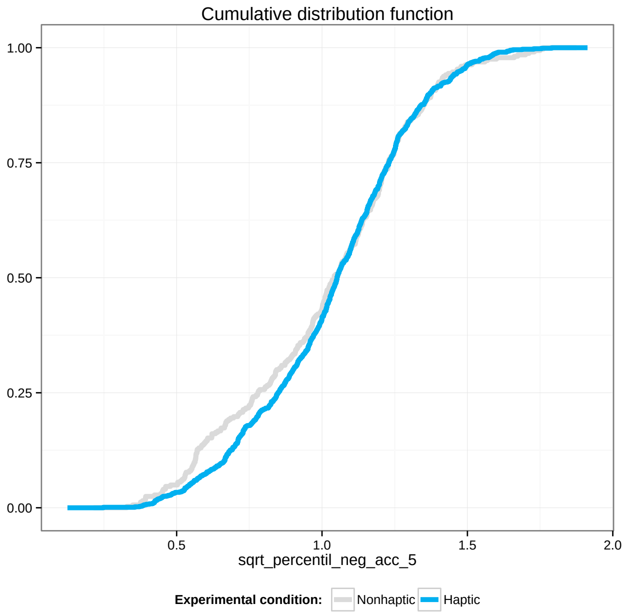


Figure 36: Empirical cumulative density function of the transformed sqrt_percentil_neg_acc_5 for the non-haptic and haptic systems before sharp curves on urban roads.

Table 11: Model based average estimates of the transformed sqrt_percentil_neg_acc_5 for the different levels of Main effect and road type, together with Tukey multiple comparison results.

	Non-haptic	Haptic	Difference (NH-H)	Tukey multiple comparisons significance test
Urban	0.94	0.86	0.08	<0.001
Rural	0.79	0.78	0.01	0.931

Table 12: Number of observations for cars and trucks with the non-haptic and haptic system.

	Non-haptic	**Haptic**
Cars	177	781
Trucks	146	142

5.3 Statistical comparisons and associated datasets

The above process to summarise the data into manageable and smaller data sets was applied to the ecoDriver data collected at 10Hz rate during the trials. For each research question category and each specific hypothesis, there is a different need (PIs are different for example) that implies a different cleaning process of the data used. This section describes the different datasets used for the different comparisons studied.

5.3.1 Statistical comparisons

Both Energy and Driver behaviour analyses were based on similar data. The data used in the driver attention studies are not presented here as they cannot be described numerically as below. Energy related and driver behaviour hypotheses share the same analysis framework based on studying specifically a set of comparisons, from the more global one to the more specific. Figure 37 presents the main comparisons, with the corresponding name of the dataset. Each data set type is different because it is linked to different VMCs and systems. The Embedded systems (Type B) are the OEM systems and the FeDS, i.e. systems that use detailed vehicle data from the CAN bus or OBD2. In contrast, the ecoDriver App (Type D) does not use such detailed vehicle data. Further, it is worth noting that only the first global comparison can be assessed using naturalistic driving data. The dataset type has an influence on analysis reporting due to the different number of categories compared together.

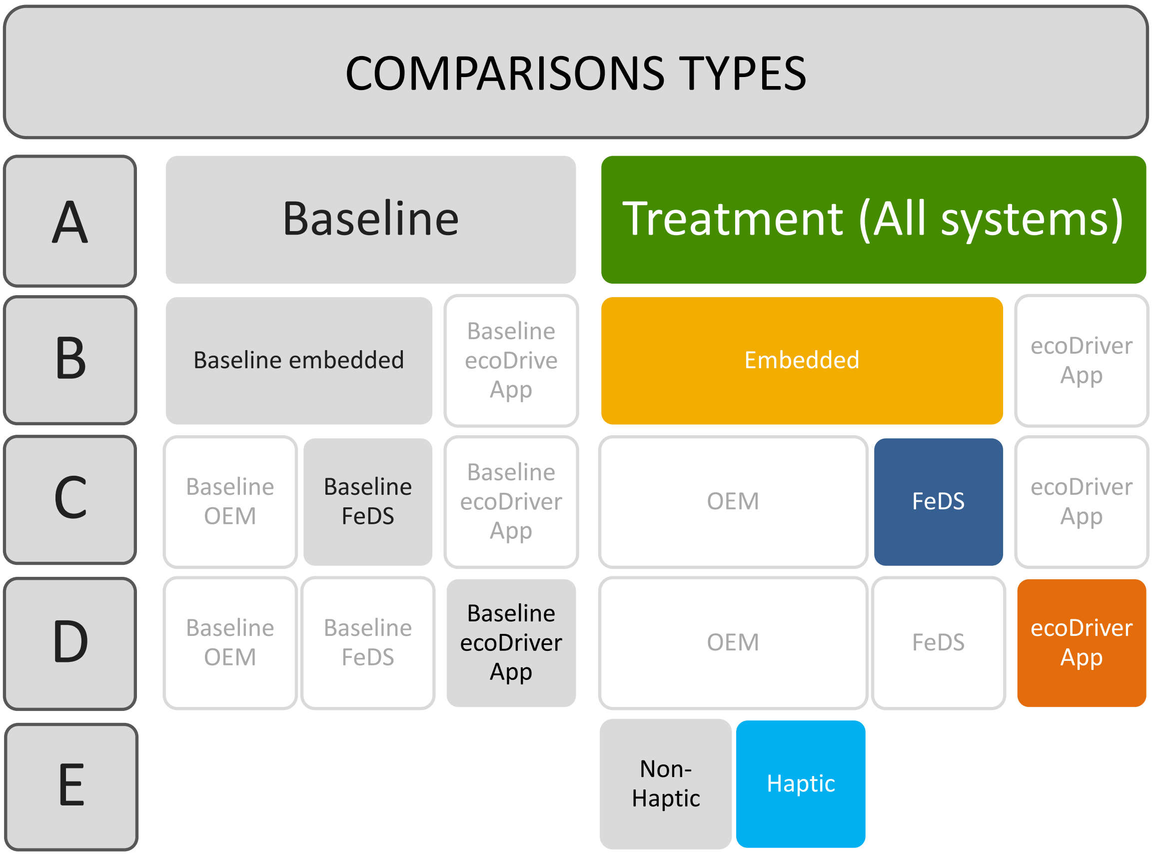


Figure 37: Overview of comparison types A through E.

The mapping between the dataset Type and VMCs contributing to each type is shown in Table 13. For comparison types A through D, the analysis consisted of *baseline versus treatment*, i.e. without versus with the given system(s). For comparison Type E, the comparison was *with versus without haptic feedback*, i.e. a system that included haptic feedback versus the same system without haptic feedback.

Each research question presented in Table 10 is therefore analysed for each of the five comparisons (Type A to E) using controlled data. Additionally, the Type A comparison is studied using only naturalistic data (see Table 14). This leads to a total of 6 different comparisons for each research question.

Table 13: Overview of VMCs contributing to comparisons A to E using controlled data

System	**VMC**	**A all systems**	**B embedded**	**C FeDS**	**D ecoDriver App**	**E Haptic**
BMW	BMW	⇔	⇔			
CRF	CRF	⇔	⇔			⇔
Daimler	Daimler	⇔	⇔			⇔
ecoDriver App	IFSTTAR	⇔			⇔	
	CTAG	⇔			⇔	
FeDS	CTAG	⇔	⇔	⇔		
	IKA	⇔	⇔	⇔		
	VTI	⇔	⇔	⇔		

Table 14: Overview of VMCs contributing to comparison A using naturalistic data

System	**VMC**	**A all**
ecoDriver App	IFSTTAR	⇔
	CTAG	⇔

Several VMCs contributed to naturalistic data collection with different purposes and systems. TomTom used a particular experimental design to observe a cohort of professional drivers while testing several versions of the envisioned system. Daimler recruited a small number of truck drivers for a limited time under natural conditions. Additionally, partners tested the ecoDriver App in real conditions with instrumented vehicles. The differences between these different approaches made it impossible to provide a common analysis.

The TomTom naturalistic data proved to be very problematic after careful analysis. Our investigation confirmed a large difference in traffic volumes between the two experimental phases of this design, and so the drivers were operating under different traffic conditions.

It has therefore been decided to exclude both Daimler (due to small sample sizes) and TomTom data temporarily from the analysis of naturalistic results.

The statistical results will be presented in tables similar to Table 15. Non-significant comparisons are uncoloured and denoted with a (N.S). When a comparison is statistically significant, the cell is coloured, depending on the effect size. Green indicates a positive effect when using the ecoDriver systems, while red indicates a negative effect. The darker the green or red, the stronger is the effect.

In order to aid the reader at this point, based on the dummy data in Table 15, we now present an example of the conclusions that could be made. Note these, are not the reported effects and are simply presented by way of illustration. Thus, with regards to Performance Indicator XXX and compared to baseline:

- In the controlled drives, the FeDS did not have an effect on urban roads (- 0.14%)
- In the controlled drives, the Embedded systems had a strong significant negative effect (-9.02%)
- Across all road types in controlled drives, the App had a strong positive effect (3.99%)
- In the controlled drives, across all systems, the positive effect was stronger on rural roads (6.74%) than on urban roads (3.52%)
- In the controlled drives, across all road types the haptic system had a slight negative effect (-2.13%), but was beneficial on rural roads (1.67%)
- On urban roads, the App was much more beneficial in the naturalistic trials (13.25%) compared to in the controlled drives (2.45%)

Table 15: Example of presentation of results (not real data, for illustration purposes only)

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					**Naturalistic**
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
XXX	XXX	Urban	3.52	-	0.14 (N.S)	2.45	-	13.25
		Rural	6.74	-9.02	-	-	1.67	-
		Motorway	-	-	-	-	-	-
		All road types	-	-	-	3.99	-2.13	-

5.3.2 Data cleaning

A common cleaning process has been defined among ecoDriver partners. This common process is followed by a hypothesis-specific additional cleaning to be performed by the analyst in charge of this question. This specific cleaning is described in the annexes devoted to detailed results of each research question. As an example, a hypothesis-specific cleaning could be necessary to exclude segments where the PI (specific to the hypothesis) is not available. The main common cleaning steps were:

- Step 1: Exclude numerical artefacts outliers (segments with short durations or wrong distance).
- Step 2: Exclude segments with unknown speed limit or road type.
- Step 3: When working with 500 meter segments, exclude the baseline-after condition, and exclude segments with duration lower than 10 seconds (which correspond to a speed>200km/h, which is unlikely).
- Step 4: The obtained dataset is then subdivided into relevant datasets for each one of the desired comparisons

Note that, due to Step 3, the default baseline condition used in the analyses is ‘baseline-before’, and not ‘baseline-after’ treatment.

5.3.3 Datasets contents

This section provides a description of the size of the six main datasets (Type A-E for controlled data, and Type A for naturalistic data) obtained after applying the data reduction process, and the above cleaning steps. The size of the datasets is presented in terms of the number of kilometres and the number of drivers, both by road Type And by baseline/treatment. The number of events and situations available for analysis are presented as well.

5.3.3.1 Controlled data

Table 16 through **Error! Reference source not found.** show the contents of the datasets used in the analysis of the controlled drives.

Table 16: Content of each dataset types

Dataset	**Road type**	**Baseline**		**Treatment**	
Type A All systems		Kilometres	Drivers	Kilometres	Drivers
	Urban	1884	142	4604	137
	Rural	2894	142	6163	137
	Motorway	894	56	2299	57
Dataset	**Road type**	**Baseline embedded**		**Embedded**	
Type B Embedded		Kilometres	Drivers	Kilometres	Drivers
	Urban	1407	102	4247	102
	Rural	2088	102	5586	102
	Motorway	894	56	2299	57
Dataset	**Road type**	**Baseline FeDS**		**FeDS**	
Type C FeDS		Kilometres	Drivers	Kilometres	Drivers
	Urban	693	58	1416	58
	Rural	1109	58	2401	58
	Motorway	810	42	1863	42
Dataset	**Road type**	**Baseline App**		**App**	
Type D App		Kilometres	Drivers	Kilometres	Drivers
	Urban	1884	142	4604	137
	Rural	2894	142	6163	137
	Motorway	894	56	2299	57
Dataset	**Road type**	**Baseline haptic**		**Haptic**	
Type E Haptic		Kilometres	Drivers	Kilometres	Drivers
	Urban	1884	142	4604	137
	Rural	2894	142	6163	137
	Motorway	894	56	2299	57

Table 17: Number of events and situations available for each comparison types analysis

Dataset	Events	Baseline	Treatment
Type A All systems	Number of intersections	22160	70622
	Number of Zebra crossings	21236	33595
	Number of Speed reducing measures	2394	3410
	Number of Sharp curves	3083	8351
	Number of Crests	451	847
	Number of Speed limit changes going down	2946	7262
Dataset	**Events**	**Baseline embedded**	**Embedded**
Type B Embedded	Number of intersections	21601	69635
	Number of Zebra crossings	5344	22053
	Number of Speed reducing measures	607	1943
	Number of Sharp curves	2185	7646
	Number of Crests	336	772
	Number of Speed limit changes going down	1948	6507
Dataset	**Events**	**Baseline FeDS**	**FeDS**
Type C FeDS	Number of intersections	9890	19994
	Number of Zebra crossings	1635	3370
	Number of Speed reducing measures	370	714
	Number of Sharp curves	688	1439
	Number of Crests	297	586
	Number of Speed limit changes going down	905	1856
Dataset	**Events**	**Baseline App**	**App**
Type D App	Number of intersections	559	987
	Number of Zebra crossings	15892	11542
	Number of Speed reducing measures	1787	1467
	Number of Sharp curves	898	705
	Number of Crests	115	75
	Number of Speed limit changes going down	998	755
Dataset	**Events**	**Baseline haptic**	**Haptic**
Type E Haptic	Number of intersections	5070	14864
	Number of Zebra crossings	1384	5564
	Number of Speed reducing measures	86	370

Dataset	Events	Baseline	Treatment
	Number of Sharp curves	826	1989
	Number of Crests	12	55
	Number of Speed limit changes going down	376	1331

5.3.3.2 *Naturalistic data*

Only the non-embedded systems were tested using a naturalistic driving approach. As the haptic systems are obviously embedded, only the comparison between baseline and treatment can be performed using the naturalistic data. Data quantities are shown in Table 18.

Table 18: Content of the naturalistic dataset used to compare the ecoDriver nomadic systems with the normal driving situation (baseline)

	Baseline		Treatment	
	Kilometres	Drivers	Kilometres	Drivers
Urban	2068	20	1865	19
Rural	2291	18	2134	18
Motorway	3207	17	2427	17

5.3.3.3 *Overview of all datasets*

The naturalistic data presented below contains only the data collected at IFSTTAR and CTAG with the ecoDriver Application. As summarised in Figure 37 the “All system” data set includes data from App, and embedded systems. Embedded systems data set includes FeDS and haptic versions. The number of kilometres analysed by road type, experimental phase and system category are shown in Figure 38.

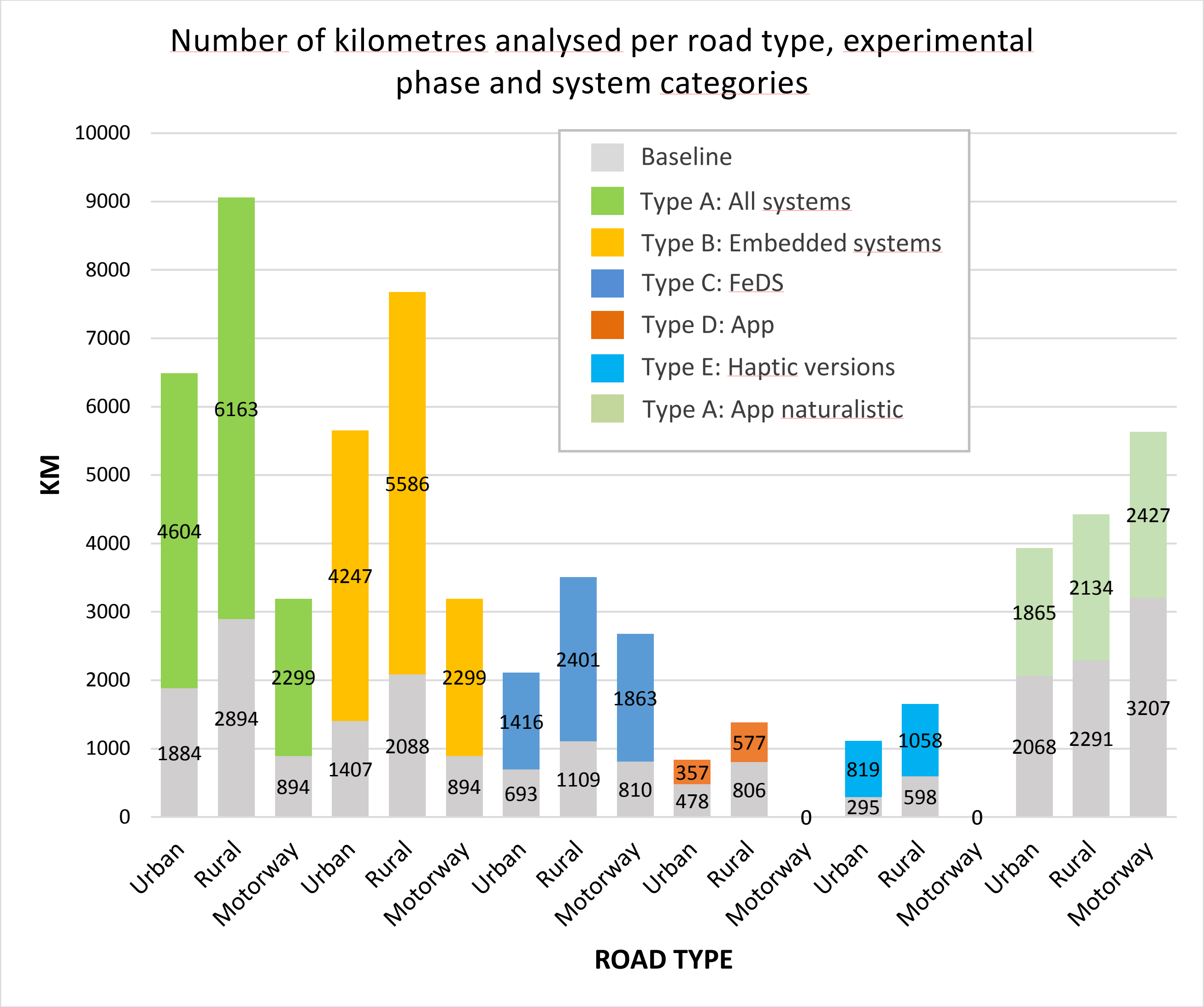


Figure 38: Kms analysed by road type, experimental phase and system categories

6 Results for energy and emissions

This chapter presents the results for the three energy-related hypotheses. In order to compare the results of the different hypotheses, it is necessary to convert the change in PI into comparable values such as percentages. The values presented in different sections represent the percentage change from the baseline to treatment. The detailed results for all the following hypotheses are provided in Annex E. The results reported below are *statistically significant* differences. When no statistical difference is found it does not mean that there is in reality no effect. It can also mean that the power of our test is not strong enough to show reliably a statistical difference.

6.1 Hypothesis 1: Using an ecoDriver system will reduce the average fuel consumption and CO_2 emissions

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
1 Energy	% of reduction for fuel consumption & CO2	Urban	2.58	2.98	-1.28 (N.S.)	1.54 (N.S.)	3.12 (N.S.)	-1.57 (N.S.)
		Rural	5.76	6.03	2.66	3.15 (N.S.)	2.83 (N.S.)	-2.49 (N.S.)
		Motorway	2.21 (N.S.)	2.24 (N.S.)	1.53 (N.S.)	-	-	0.3 (N.S.)
		All road types	4.2	4.38	1.46	2.54	2.73 (N.S.)	-0.8 (N.S.)

The analysis was carried out using acquired or modelled fuel consumption. The Performance Indicator used is the percentage reduction (or increase) in fuel consumption with respect to the average fuel consumption of the same driver in the same road type during baseline.

The use of the ecoDriver systems reduces significantly fuel consumption and CO_2 emission for all systems. Using the controlled data, the average impact is 4.2% (4.2% considering average of chunks, 4.4% considering trips). The percentage of reduction on urban roads is on average 2.6%, on rural roads 5.8% and on motorways 2.2%. The difference between baseline and treatment is significant on urban and rural roads only. The effect is generally slightly stronger with embedded systems. The poorer performance for the FeDS on motorways can most likely be explained by the decision that advised speed should be 100 km/h for speed limits over 100 km/h.

It is also worth noting that some drivers achieved considerably greater savings than the overall mean. Ten percent of drivers saved more than 13% of fuel and 5% of drivers saved more than 20%.

The ecoDriver systems' positive impact was not significantly increased by a haptic pedal. However, the sample is small and possibly high in variability due to the chunking analysis. Also on these small segments the impact of parameters such as slope was not considered and may be important. An analysis carried out at the trip level found a similar, but in this case also statistically significant, additional impact of the haptic pedal (3.2%).

The impact of systems is not significant in naturalistic driving tests. Here, the average impact is not so different from the impact of the App in controlled test for urban and rural condition, but the lack of statistical significance could be due to the high dispersion of data and smaller impact of systems on motorway. In the naturalistic testing of the hybrid bus system, again the impact of the system on fuel consumption was not significant. However, there was evidence of a non-significant tendency for fuel consumption to reduce by 5.2% when interacting with the system.

6.2 Hypothesis 2: Using an ecoDriver system will reduce the average energy consumption

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
2 Energy	% of energy consumption reduction	Urban	-	-	-9.24 (N.S.)	-	-	-
		Rural	-	-	3.16 (N.S.)	-	-	-
		Motorway	-	-	6.72 (N.S.)	-	-	-
		All road types	-	-	-0.38 (N.S.)	-	-	-

The analysis was only carried out for one site and one electric vehicle. The Performance Indicator used is the percentage reduction (or increase) in energy use with respect to the average energy consumption of the same driver in the same road type during baseline. The sample was very small and the results do not highlight significance in differences between baseline and treatment on chunks, whereas a significant impact is highlighted by the analysis on trips.

6.3 Hypothesis 3: Using an ecoDriver system will reduce the average NOx emissions

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
3 Energy	% of NoX reduction compared to resp. baseline	Urban	2.61	3.27	1.64 (N.S.)	-0.28 (N.S.)	1.77 (N.S.)	-1.07 (N.S.)
		Rural	5.11	5.65	4.09	2.35 (N.S.)	0.1 (N.S.)	-0.9 (N.S.)
		Motorway	3.29	3.34	2.79 (N.S.)	-	-	3.44
		All road types	4.04	4.49	3.18	1.34 (N.S.)	0.67 (N.S.)	0.97 (N.S.)

The analysis was carried out considering NOx emission estimated by the model. The Performance Indicator used is percentage of NOx reduction/increasing with respect to the average NOx emission of the same driver in the same road type during baseline.

The usage of the ecoDriver systems reduces NOx emission on all road types. The average NOx reduction due to the systems is 4%. The percentage of reduction on urban roads is on average 2.6%, on rural roads 5.1% and on the motorway 3.3%. The effect is generally slightly stronger with embedded systems, whilst for FeDS the effect is globally significant and on rural roads. For the App no significant impact emerged, but it is important to highlight that the sample is smaller and the system was tested in only one site. The ecoDriver systems positive impact is not significantly increased by the haptic pedal but also in this case the sample is small. In naturalistic driving the impact is significant in motorway, but it is important to highlight the high dispersion of data that can have had an impact on results.

6.4 Summary

ENERGY

- Using an ecoDriver system will reduce the average fuel consumption & CO_2 emissions (per 100km).
- Using an ecoDriver system will reduce the average NOx emissions (per 100km).
- Using an ecoDriver system will reduce the average energy consumption (per km or 100km).

Table 19: Summary of results for energy analysis

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
1 Energy	% of reduction for fuel consumption & CO2	Urban	2.58	2.98	-1.28 (N.S.)	1.54 (N.S.)	3.12 (N.S.)	-1.57 (N.S.)
		Rural	5.76	6.03	2.66	3.15 (N.S.)	2.83 (N.S.)	-2.49 (N.S.)
		Motorway	2.21 (N.S.)	2.24 (N.S.)	1.53 (N.S.)	-	-	0.3 (N.S.)
		All road types	4.20	4.38	1.46	2.54	2.73 (N.S.)	-0.8 (N.S.)
2 Energy	% of energy consumption reduction	Urban	-	-	-9.24 (N.S.)	-	-	-
		Rural	-	-	3.16 (N.S.)	-	-	-
		Motorway	-	-	6.72 (N.S.)	-	-	-
		All road types	-	-	-0.38 (N.S.)	-	-	-
3 Energy	% of NoX reduction compared to resp. baseline	Urban	2.61	3.27	1.64 (N.S.)	-0.28 (N.S.)	1.77 (N.S.)	-1.07 (N.S.)
		Rural	5.11	5.65	4.09	2.35 (N.S.)	0.1 (N.S.)	-0.9 (N.S.)
		Motorway	3.29	3.34	2.79 (N.S.)	-	-	3.44
		All road types	4.04	4.49	3.18	1.34 (N.S.)	0.67 (N.S.)	0.97 (N.S.)

6.4.1 Results combining all systems

The systems tested were very different from each other, so that when they are all considered together, they offer a good opportunity for a robust vision of their impact in real life conditions. For energy consumption and CO_2, the systems cause an average reduction of 4.2%; considering different road types the reductions ranged from 2.2% (non-significant reduction of energy on motorway roads where the sample is smaller) to 5.8% (significant reduction of energy on rural roads). Reductions in NOx emissions have a similar average value 4% and are significant on all road types ranging from 2.6% (urban) to 5.1% (rural). In the naturalistic data, a significant reduction of NOx emissions of 3.4% on motorways is found.

6.4.2 Results across road types

The ecoDriver systems reduced fuel consumption and CO_2 emissions by up to 5.76% (rural, embedded), with more impact on rural roads. It will be recalled that, for the FeDS, the design decision was made that advised speed should be 100 km/h for speed limits over 100 km/h. This most likely affected fuel savings on motorways. The same tendency for a bigger impact on rural roads is present for NOx reduction, with a saving of up to 5.1% on rural roads.

6.4.3 Results across system categories

The ecoDriver embedded systems (that use detailed vehicle data from the CAN bus or OBD2) perform better than the App system with fuel savings of up to 6% on urban roads. Individually, the FeDS had a significant impact on both fuel/CO_2 and NOx with an average saving of 1.5% and 3.2% respectively and with a saving up to 2.7% and 4.1% on rural roads. The App reduces significantly fuel consumption with an average fuel saving of 2.5%. The haptic systems in addition to visual system reduces consumption by up to 3%, but we lack evidence to extrapolate these results. In the naturalistic testing of the hybrid bus system, there was no significant reduction in fuel consumption during system use, although there was a non-significant tendency in an encouraging direction.

7 Results for driver workload and attention

7.1 Hypotheses 4 and 5: Using an ecoDriver system will increase driver workload

This section reports on the drivers' subjective ratings of their workload when using an ecoDriver system. Across all studies, drivers were requested to rate their workload using the NASA-TLX workload scales, both during the baseline drives and during the experimental drives with an ecoDriver system. The NASA-TLX is comprised of 6 subscales (mental demand, physical demand, temporal demand, overall performance, effort, and frustration). These subscales can be summed to produce a total workload score (maximum 60). The total workload score is the metric discussed in this section.

Workload data collection was not consistent across VMCs, with different VMCs collecting ratings after different durations of exposure to an ecoDriver system. Furthermore, between trials, there were small differences in experimental design (e.g. number and duration of baseline and experimental phases). This hinders statistical comparison between baseline and experimental drives, which involves data from multiple VMCs. As a result, the presentation below is restricted to a descriptive analysis of the subjective workload data. Table 20 shows the number of completed workload questionnaires that were available at each stage of the ecoDriver studies.

Table 20: Completed workload questionnaires per system type

System Type	Baseline 1	Exposure 1	Exposure 2
FeDS	22	22	22
App	32	31	31
Embedded	57	58	69
Non-embedded	32	31	31

Figure 39 shows that across all system types, the ecoDriver system did not cause a substantial increase in total driver workload.

For the FeDS system, mean driver workload in the baseline condition was 11.2, with a slight increase to 14.0 at the first workload measurement during system exposure. Workload ratings were similar for the second measurement during system exposure (mean = 13.4). For the ecoDriver App, a similar pattern was observed, with mean workload rated at 12.4 during the baseline drive, then 13.5 for both the first and second workload measurements during system exposure. For the dataset including all embedded systems (FeDS + OEM systems), mean total workload in the baseline condition was 14.7, with this rising slightly to 18.1 and 18.4 at the first and second exposure measurements. The ecoDriver App and non-embedded datasets were identical for this metric. Across all system types, there was evidence to suggest that workload ratings dropped as exposure increased, however limited data was available for prolonged system use (n = 4 for the FeDS system, n = 22 for the ecoDriver App).

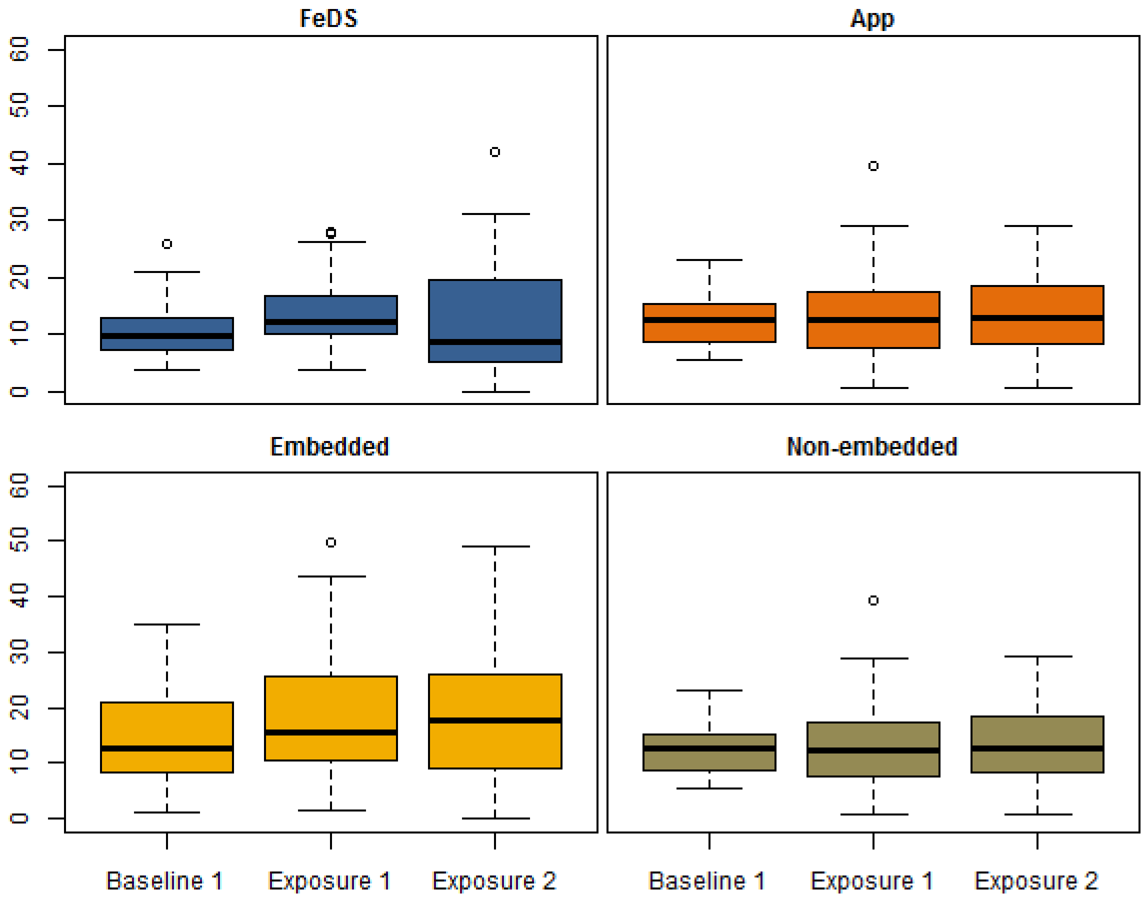


Figure 39: Total NASA-TLX Workload Score (max. 60)

Overall, the subjective evidence is encouraging in that drivers do not perceive more than a very small increase in overall workload when interacting with an ecoDriver system during driving. This suggests that the systems have been designed in a way that avoids increasing the demand of the everyday driving task.

7.2 Hypotheses 6, 7 and 8: Using an ecoDriver system will decrease driver attention

This section deals with the drivers' visual interaction with the Full ecoDriver System (FeDS). It investigates how drivers interact with the system, if and in that case to which extent they might lose track of traffic related targets, and also the visual information intake in relation to the speedometer.

Eye tracking data were only collected at the Swedish VMC. Ten participants took part in a controlled test, during which they drove the same route nine times over the course of approximately one year, to account for seasonal effects. The first two drives were baseline drives without FeDS, the next five drives were treatment drives with the FeDS in place, and the last two drives were after-exposure baseline drives without FeDS. The last drive was conducted at least four weeks after the next-to-last drive, to investigate the persistence of learning effects.

The FeDS has a visual user interface, hence it has to be expected that the participants will glance at the display. Therefore, when investigating whether such a system is safety critical or not, the question should be how well drivers integrate their glancing at the system into their general glance behaviour while driving. Indications for dangerous glance behaviour might be a decreased glance activity to mirrors and the speedometer due to focus being directed at the FeDS instead. Eye tracking data were collected at the Swedish VMC over the course of one year, including two baseline drives, five treatment drives with the FeDS, and two post baseline drives.

Overall, glances towards the FeDS were shorter and fewer, and clusters of several glances were used less frequently with increased familiarity with the system (Figure 40). The overall time spent looking away from the road was, however, larger with the FeDS present than when it was absent, and possibly somewhat larger in the baseline drives after having experienced the FeDS than before. Even though the FeDS obviously and clearly receives visual attention, it is important to note that drivers do not neglect to glance at the mirrors or the speedometer. The glance intensity to the FeDS is comparable to what is found for the speedometer, such that it cannot be said to be extraordinarily high.

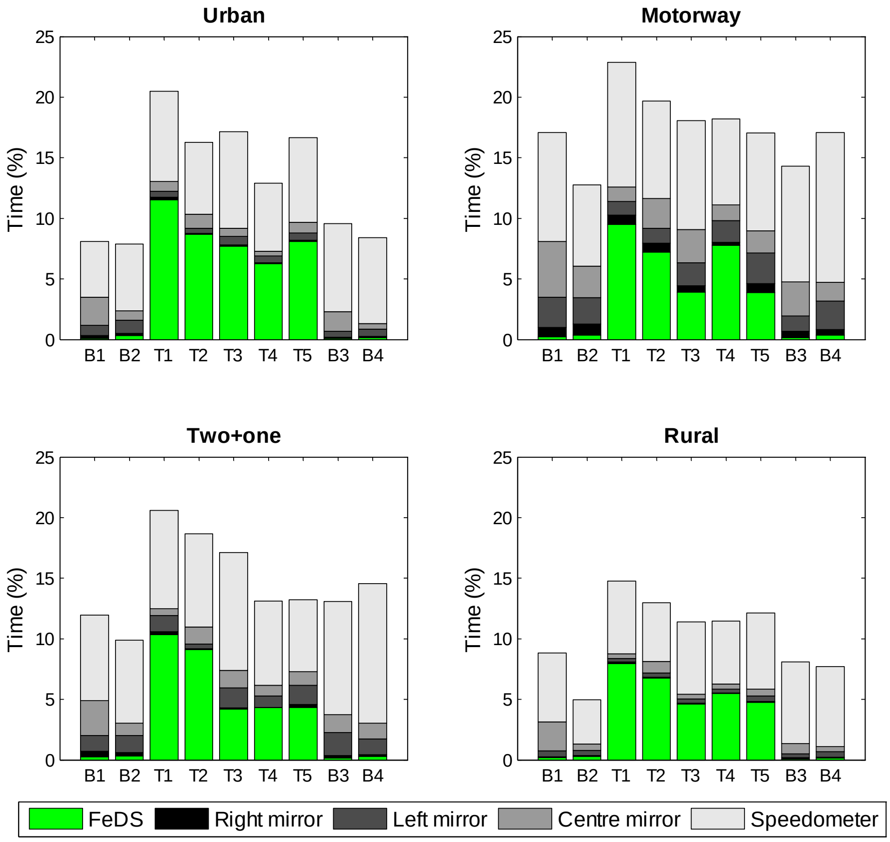


Figure 40. Percentage of glances to different targets per trip per road type.

The distraction detection algorithm AttenD (Kircher and Ahlstrom, 2010; Kircher and Ahlstrom, 2013) indicate that the number of distraction events per kilometre was higher in the treatment drives than in the baseline drives on urban roads. It is however well known that AttenD makes mistakes in low speeds, especially in complex environments. Also, data obtained from motorway driving indicate that glances towards the FeDS are likely within the available visual spare capacity. This will have to be investigated further for other road types as well.

In certain traffic situations the drivers are provided with advice (visual information accompanied by an auditory beep), followed by feedback (visual information only) via popup information. There is a clear difference in how drivers treat these different types of popups, Figure 41. Before the advice is given, the FeDS is glanced at sporadically. When the auditory cue is provided, the display is glanced at in the following six seconds in about 70 % of the cases, which is much more than without the auditory cue. Without the auditory cue, but the mental expectation of an upcoming feedback, the FeDS is glanced at more before the feedback occurs, which indicates a form of readiness or expectation. This situation could be improved. The goal should be to provide information that is easily accessible, that makes itself known when it is present, but that is not too compelling. Possible alternatives could be to always allow the driver to access the information that was presented last or to allow an optional sound signal, as for the advice.

The data show (Figure 40) that the speedometer is an important asset in the pursuit of an eco-friendly driving style, so it is advisable to integrate the eco-support system with the speedometer. This is likely to reduce the percentage of glances away from traffic, and the driver does not have to integrate information from two different displays, which might entail an unnecessary increase in workload.

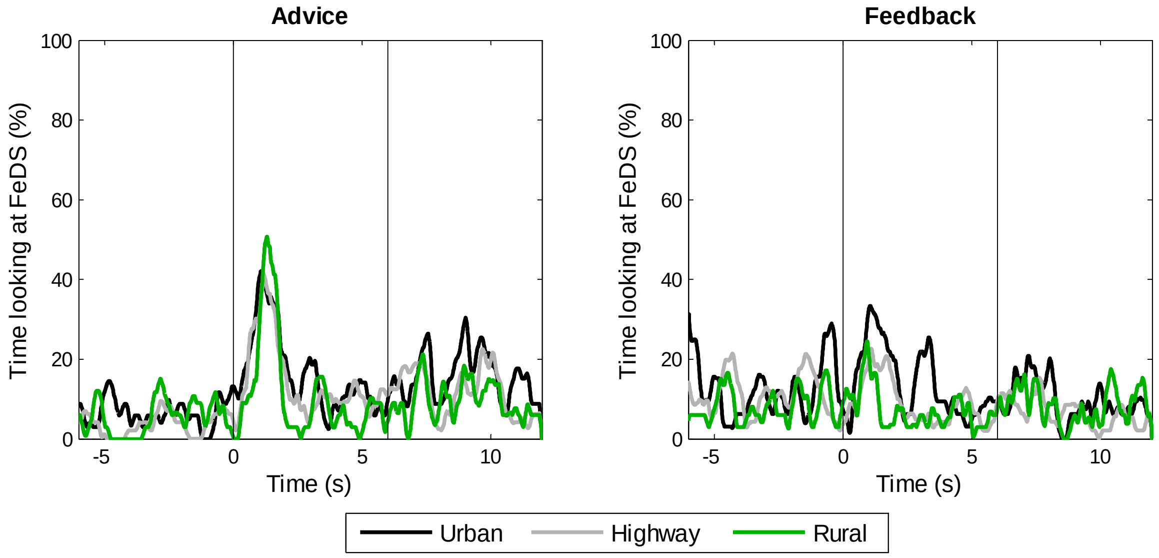


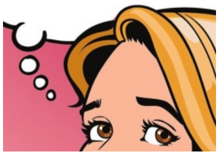
Figure 41. Percentage of time looking at FeDS per road Type As a function of time. The vertical lines corresponds to the advice/feedback popup (t = 0 seconds) and when the popup disappears (t = 6 seconds).

7.3 Summary

WORKLOAD

- Using an ecoDriver system , driver workload will increase
- Workload varies across the different ecoDriver system types

There was no evidence to suggest that any of the ecoDriver systems tested caused a substantial increase in subjective driver workload. Across all system types, there was only a very small increase in total workload when interacting with the system, with some tentative evidence to suggest that workload may decrease with increasing exposure.



ATTENTION

- Using an ecoDriver system with in-trip feedback, the drivers are more distracted
- In-car feedback from the ecoDriver system cause inappropriate/dangerous visual behaviour, in terms of glances towards the device
- Using an ecoDriver system, the driver will look more at the speedometer/rev counter

Most systems tested have a visual user interface aimed to attract visual attention. Attentional effects were investigated with only the FeDS. The overall time spent looking away from the forward roadway was found to be larger with the FeDS. However, drivers did not neglect to glance at the mirrors or speedometer, and data obtained from motorway driving indicate that glances towards the FeDS are likely within the available visual spare capacity. Glance patterns indicated that drivers were anticipating feedback from the FeDS, which indicates the HMI can be improved to reduce workload. Thus, it is advisable to integrate the eco-support system with the speedometer.

8 Results for driver behaviour

8.1 Introduction

With respect to driving behaviour the hypotheses were mainly related to longitudinal behaviour (speed, acceleration / deceleration and time headway). Also hypotheses were tested with respect to the golden rules of eco-driving. The results presented are again colour coded. Positive values indicate a positive 'effect'. The colour indicates whether the effect was significant or nor. Green colours indicate a positive significant effect (darker green indicates a larger effect) and 'red' colours indicate a negative significant effect (the more red the larger the effect). No colour indicates a non-statistical significant difference or the absence of data. The detailed results for all the following hypotheses are provided in Annex G. The results reported below are statistically significant differences. When no statistical difference is found it does not mean that there is in reality no effect. It can also mean that the power of our test is not strong enough to show reliably a statistical difference.

Among the effects that can lower the positive impact of a driving assistance system, the learning effect is the biggest. The impact of a long term exposure to an eco-driving system has been studied previously (Beusen et al. 2009), and large differences across drivers were observed. Most drivers improved their driving style on the long term, while others fall back into their original driving habits. Such differences across drivers have not been studied in our work, but this kind of behaviour certainly lower the significance of our findings.

8.2 Hypothesis 9: Using an ecoDriver system the average velocity when cruising will be lower

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
9 Speed	Average speed when cruising	Urban	-2.79	3.30	4.76	-8.86 (N.S.)	3.63	3.28
		Rural	4.04	1.82	1.71 (N.S.)	2.17 (N.S.)	-0.95 (N.S.)	0.03 (N.S.)
		Motorway	3.42	3.32	3.50	-	-	1.25
		All road types	2.39	2.53	2.95	-	0.74 (N.S.)	1.24

Overall, the use of the ecoDriver systems reduced average cruising speed. One notable exception when taking all systems into account is a higher expected average speed with the ecoDriver systems on urban roads. This effect however seems not to have occurred in all drives, since for other systems the overall effect is that cruising speed is reduced, generally about 2-4%. The App (android application) ecoDriver system did not show significant reduction in average cruising speed; however this subset of the data did have the smallest dataset (3638 segments). The haptic ecoDriver system reduced cruising speed in urban settings by 3.6% compared to the non-haptic version of the ecoDriver system. The ecoDriver system in naturalistic drives reduced average cruising speed with 8.5% on urban roads, and 4.5% on highways. Overall, the lower average cruising speeds will translate into safer roads if the ecoDriver system is widely implemented.

8.3 Hypothesis 10: Using an ecoDriver system the average free velocity will be lower

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
10 Speed	Average speed when freely driving	**Urban**	3.07 (N.S.)	10.61	9.83	0.45 (N.S.)	-11.87 (N.S.)	-
		Rural	3.55	0.37 (N.S.)	0.37 (N.S.)	1.31 (N.S.)	-0.05 (N.S.)	-
		Motorway	0.57 (N.S.)	0.67 (N.S.)	0.62 (N.S.)	-	-	-
		All road types	2.97	4.06	2.78	1.18 (N.S.)	4.84 (N.S.)	-

When filtering to keep only segments with >50% free driving, 6,516 segments are used in the analysis (all systems, controlled). This is much less data than for other PIs (e.g., 33,136 for cruising speed, all systems, controlled). This relatively small sample potentially caused the majority of analyses to be statistically insignificant. However, when an effect was significant, it was often quite large, ranging from a 3.6% to a 10.6% reduction in average free-driving speed. For the systems overall, this effect was on rural roads (2.7%), while when considering specific systems, embedded and FeDS ecoDriver systems showed significant reduction in average speed during free driving on urban roads (10.6% and 9.8% respectively). The effects found to be significant are substantial compared to other speed related driver performance indicators (e.g. hypothesis 14, related to cruising speed). The current results indicate that when the ecoDriver system has effect on driving behaviour in these conditions, it can be substantial in lowering average speeds

8.4 Hypothesis 11: Using an ecoDriver system, the speed will change before intersections without traffic lights

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
11 Speed Situations	avg_speed_ distance_ based before intersections	Urban	-3.14	-0.13 (N.S.)	2.76	-1.4 (N.S.)	1.1 (N.S.)	-
		Rural	5.60	3.47	1.82	1.78	1.22 (N.S.)	-
		Motorway	5.08	5.01	2.57	-	-	-
		All road types	1.32	1.66	1.58	-0.61 (N.S.)	1.00	-

If the ecoDriver systems effectively improved green driving behaviour on the approach to intersections without traffic lights, a reduction in average vehicle speed on the 300m approach to this event would be expected. Overall, the use of an ecoDriver system significantly reduced vehicle speed before intersections without traffic lights. Across all systems combined, there was a significant reduction in speed of 0.7 km/h when the data was pooled across all road types. The speed reduction was largest on motorways (4.8 km/h) and second largest on rural roads (3.4 km/h). The full ecoDriver system produced a significant reduction in speeds across all road types, urban, rural and motorway, with the largest effect on motorways. For the comparisons involving all embedded systems, the reduction in approach speeds brought about by these system was significant on rural roads and motorways only. The ecoDriver application also caused a significant reduction in speeds before intersections, however, the effect was significant on rural roads only. The haptic system produced a significant speed reduction when approaching intersections in comparison to the non-haptic system. Overall, there is evidence that all versions of the ecoDriver system can have a positive effect on safety by reducing vehicle speeds on the approach to intersections without traffic lights. This could translate into a significant road safety improvement with wider uptake of the system.

8.5 Hypothesis 12: Using an ecoDriver system, the speed will change before zebra crossings

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
12 Speed Situations	avg_speed_ distance_ based before zebra crossings	Urban	-0.99 (N.S.)	2.33	4.18	0.49 (N.S.)	0.07 (N.S.)	-
		Rural	13.13	2.43 (N.S.)	3.47 (N.S.)	3.18	-1.83 (N.S.)	-
		Motorway	7.6 (N.S.)	7.58 (N.S.)	7.19 (N.S.)	-	-	-
		All road types	1.29	2.22	3.53	0.59 (N.S.)	-0.08 (N.S.)	-

A reduction in speed before zebra crossings was expected if the ecoDriver system was successful in improving green driving behaviour around these events. However, it should be noted that none of the ecoDriver systems gave zebra crossing-specific advice, and so any impact of the system would likely be due to global impacts on green driving behaviour. Overall, the results suggest a positive effect of the ecoDriver systems on average vehicle speed when approaching zebra crossings. The different types of systems show different effects on urban and rural roads. For example, the analysis of all ecoDriver systems shows a significant reduction in vehicle speeds of 6.4 km/h before zebra crossings on rural roads, but no significant effect on vehicle speeds on urban roads. This is mirrored by the effect of the ecoDriver application, whose speed reducing effect was greater on rural roads. In contrast, the impact of the embedded systems was significant on urban roads only, with a speed reduction of 0.8 km/h seen when driving with the system compared to driving without it. The full ecoDriver system showed a similar pattern of effects, with system use causing a 1.5 km/h drop in speed compared to no system use, before urban zebra crossings only. For zebra crossing events, the addition of a haptic pedal to the ecoDriver system did not have an impact on driver behaviour. Overall, there is evidence that all versions of the ecoDriver system can have a positive effect on vehicle speeds at zebra crossings on particular road types, which should translate into a measurable improvement of both driver and pedestrian safety.

8.6 Hypothesis 13: Using an ecoDriver system, the speed will change before speedbumps

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
13 Speed Situations	avg_speed_ distance_ based before speedbumps	Urban	1.1 (N.S.)	2.26 (N.S.)	1.32 (N.S.)	0.6 (N.S.)	-6.61 (N.S.)	-
		Rural	0.99 (N.S.)	1.65 (N.S.)	1.88 (N.S.)	-0.12 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	0.77 (N.S.)	1.46 (N.S.)	0.37 (N.S.)	-0.12 (N.S.)	-6.61 (N.S.)	-

None of the ecoDriver systems provided advice that was specific to speedbump events, and so no a priori predictions were made regarding the expected impact of the system on vehicle speeds when approaching these events. Overall, there was no significant impact of any ecoDriver system type on average vehicle speed immediately before a speedbump. Interestingly, an analysis of spot speeds at the speedbump showed a non-significant tendency for vehicle speeds to be higher at speedbumps when driving with the system compared to driving without it. This was true across all system types, with the increase in speed being as large as 1.9 km/h on urban roads when using the FeDS. This perhaps suggests that drivers were choosing to maintain their speed rather than slowing down for the speedbumps, in keeping with one of the golden rules of eco-driving, to maintain a steady speed at low RPM. There was a significant impact of the haptic pedal on vehicle speeds on the approach to speedbumps. However, a trend for slightly higher speeds (a 2.1 km/h increase) was observed on urban roads when driving with the haptic pedal compared to without it. This analysis may have suffered from the low statistical power brought about from the small number of cases involved (n = 179). In fact, more generally, each analysis of vehicle speeds before speedbumps had a low number of cases (n = 523-2684 cases), which will have reduced the likelihood of detecting small significant effects of system on driver behaviour.

8.7 Hypothesis 14: Using an ecoDriver system, the speed will change before sharp curves

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
14 Speed Situations	avg_speed_ distance_based before sharp curves	Urban	-2.38 (N.S.)	1.35 (N.S.)	1.85 (N.S.)	3.26 (N.S.)	4.96	-
		Rural	3.72	2.45	3.40	1.35 (N.S.)	-1.46 (N.S.)	-
		Motorway	0.44 (N.S.)	0.22 (N.S.)	5.1 (N.S.)	-	-	-
		All road types	1.33	1.83	2.24	-0.79 (N.S.)	1.18 (N.S.)	-

A reduction in average speed on the approach to sharp curves would be expected if the ecoDriver system was successful in improving green driving behaviour around these events. Overall, there was evidence that the use of an ecoDriver system had a significant impact on vehicle speeds on the approach to sharp curves. A significant reduction in vehicle speeds was observed on rural road curve approaches in the all systems analysis (-2.1 km/h), the embedded systems analysis (-1.4 km/h), and the full ecoDriver system analysis (-1.9 km/h). Across all analyses there was no significant reduction in curve approach speed when using an ecoDriver system on urban roads or motorways. Additionally, there was a significant reduction in approach speeds when using the haptic system compared to the non-haptic system on urban roads. It appears that on rural roads especially, the ecoDriver system lowers the speed at which drivers approach sharp curves. This could lead to a substantial improvement in road safety around these events.

8.8 Hypothesis 15: Using an ecoDriver system, the speed will change at crests

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
15 Speed Situations	avg_speed_ distance_ based at crests	Urban	0.87 (N.S.)	0.94 (N.S.)	0.69 (N.S.)	2.25 (N.S.)	2.5 (N.S.)	-
		Rural	1.25 (N.S.)	1.08 (N.S.)	0.34 (N.S.)	2.16	1.18 (N.S.)	-
		Motorway	-2.66 (N.S.)	-2.65 (N.S.)	-2.62 (N.S.)	-	-	-
		All road types	1.68	1.59 (N.S.)	1.29 (N.S.)	2.21	1.06 (N.S.)	-

Few ecoDriver systems provided guidance that was specific to driving on gradients, hence limited predictions were made about the expected effects of the system on vehicle speeds. Overall, it was observed that the use of most ecoDriver systems did not have a significant impact on vehicle speeds on gradients. There was one significant effect, with the ecoDriver application leading to significantly lower speeds on rural roads compared to the baseline condition. The application does not provide guidance relating to driving on gradients, so this effect is likely to be due to a more global impact on the drivers' green driving behaviour. There was no evidence that the addition of the haptic pedal changed vehicle speed on gradients. However, it should be noted that these analyses were conducted on a low number of cases, and as such may lack the statistical power necessary to detect small effects of the ecoDriver systems on driver performance.

8.9 Hypothesis 16: Using an ecoDriver system, the speed will change before speed limit changes

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
16 Speed Situations	avg_speed_ distance_ based before speed limit changes	Urban	1.41 (N.S.)	2.54 (N.S.)	4.2 (N.S.)	3.08 (N.S.)	1.14 (N.S.)	-
		Rural	2.30	2.36	2.35 (N.S.)	0.74 (N.S.)	-2.67 (N.S.)	-
		Motorway	6.42	6.31	4.24	-	-	-
		All road types	2.56	2.98	3.06	1.45 (N.S.)	-1.23 (N.S.)	-

The average speed on the approach to a speed limit decrease would be expected to be lower if the ecoDriver systems are effective in encouraging green driving behaviour (such as earlier adoption of coasting as a speed reduction strategy) during these events. Overall, there was evidence to suggest that the ecoDriver systems cause the driver to drive significantly slower on the approach to a speed limit decrease, compared to when they are not using a system. This effect was observed for the complete dataset, the full ecoDriver system data, and the embedded systems data. In each of these cases, approach speed was decreased on all road types, with this effect reaching significance on rural roads and motorways. There was no impact of using the ecoDriver application on vehicle speeds when approaching a speed limit decrease. The addition of a haptic component to the ecoDriver systems did not have a further impact on vehicle speeds for these speed limit change events. Overall, there is evidence that most versions of the ecoDriver system can have a positive effect on vehicle speeds on the approach to a decrease in the speed limit. This could be through encouraging drivers to release the accelerator and coast earlier during the approach phase. This effect could have a substantial positive impact on both fuel consumption and road safety with wider uptake of the system.

8.10 Hypothesis 17: Using an ecoDriver system, the time headway distribution to leading vehicle will change

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
17 THW Situations	Average time headway	Urban	6.50	11.15	12.23	3.97 (N.S.)	-	-
		Rural	5.86	5.65 (N.S.)	4.71 (N.S.)	-1.88 (N.S.)	-	-
		Motorway	8.56	9.17	12.36	-	-	-
		All road types	6.29	9.06	10.24	-0.33 (N.S.)	4.45 (N.S.)	-

Overall, THW increases in the treatment condition compared to baseline driving. This effect can be observed on all road types, but is largest on urban roads. When analysing the four different sub sets of ecoDriver systems separately, significant differences between baseline and treatment condition could only be shown for embedded systems and the FeDS. No significant differences in THW were observed for the ecoDriver App and the haptic vs. non-haptic treatment conditions. An increase of the average THW implies an increase of the average distance headway (shown as negative effect size in the table above). This means that drivers extend the gap to the vehicles in front for a better anticipation of the traffic which can improve both safety and eco-friendly predictive driving. However, this effect can only be shown for two out of four different system categories tested.

8.11 Hypothesis 18: Using an ecoDriver system, there will be shorter distances to vehicles before intersections without traffic light

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					**Naturalistic**
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
18 THW Situations	Average time headway before intersections	Urban	8.10	12.93	13.87	3.67 (N.S.)	-	-
		Rural	2.6 (N.S.)	4.58	5.45 (N.S.)	-7.63 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	5.63	9.57	10.36	-1 (N.S.)	15.23	-

Before upcoming intersections, the average THW increases in the treatment condition compared to baseline driving which implies an increase of distance to front vehicles. This effect can be observed on all road types, but is largest on urban roads. When analysing the four different subsets of ecoDriver systems separately, significant differences between baseline and treatment condition could be shown for embedded systems, the FeDS and the haptic vs. non-haptic treatment conditions. No significant differences in THW were observed for the ecoDriver App. The by far largest effect could be observed for the haptic vs. non-haptic comparison. An increase of the average THW implies an increase of the average distance headway. This means that drivers extend the gap to the vehicles in front for a better anticipation of the traffic which can improve both safety and eco-friendly predictive driving. This effect can be shown for three out of four different systems tested.

8.12 Hypothesis 19: Using an ecoDriver system, there will be shorter distances to vehicles before zebra crossings

Effect sizes in percentages (differences in % from relevant baseline)

Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
19 THW Situations	Average time headway before zebra crossings	Urban	-1.42 (N.S.)	2.87 (N.S.)	1.95 (N.S.)	-2.11 (N.S.)	-	-
		Rural	1.67 (N.S.)	-3.1 (N.S.)	-3.54 (N.S.)	4.45 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	-1.13 (N.S.)	1.42 (N.S.)	0.32 (N.S.)	-1.74 (N.S.)	11.64 (N.S.)	

Around zebra crossings, no significant effects for changes in average THW in treatment compared to baseline driving could be observed. When analysing the four different subsets of ecoDriver systems separately, also no significant differences in THW were found. An increase of the average THW implies an increase of the average distance headway. This means that drivers extend the gap to the vehicles in front for a better anticipation of the traffic which can improve both safety and eco-friendly predictive driving. However, this effect cannot be shown for any of the tested systems within the range of zebra crossings.

8.13 Hypothesis 20: Using an ecoDriver system, there will be shorter distances to vehicles before speedbumps

Effect sizes in percentages (differences in % from relevant baseline)

Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
20 THW Situations	Average time headway before speed bumps	Urban	6.77 (N.S.)	8.12 (N.S.)	8.12 (N.S.)	6.47 (N.S.)	-	-
		Rural	0.32 (N.S.)	-6.8 (N.S.)	-6.8 (N.S.)	8.06 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	4.49 (N.S.)	0.69 (N.S.)	0.69 (N.S.)	6.33 (N.S.)	-	-

Around speed reducing measures (speedbumps), no significant effects for changes in average THW in treatment compared to baseline driving could be observed. When analysing the four different subsets of ecoDriver systems separately, also no significant differences in THW were found. An increase of the average THW implies an increase of the average distance headway. This means that drivers extend the gap to the vehicles in front for a better anticipation of the traffic which can improve both safety and eco-friendly predictive driving. However, this effect cannot be shown for any of the tested systems within the range of speed reducing measures.

8.14 Hypothesis 21: Using an ecoDriver system, there will be shorter distances to vehicles before sharp curves

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
21 THW Situations	Average time headway before sharp curves	Urban	4.62 (N.S.)	16.54	22.27	0.56 (N.S.)	-	-
		Rural	7.87 (N.S.)	3.73 (N.S.)	2.73 (N.S.)	8.37 (N.S.)	-	-
		Motorway					-	-
		All road types	4.73 (N.S.)	8.36	8.68	1.32 (N.S.)		

Approaching sharp curves, no significant effects in average THW in treatment condition compared to baseline driving were found. When analysing the four different subsets of ecoDriver systems separately, significant differences between baseline and treatment condition could only be shown for embedded systems and the FeDS where the effect can be observed mainly on urban roads. No significant differences in THW were observed for the ecoDriver App and the haptic vs. non-haptic treatment conditions. An increase of the average THW implies an increase of the average distance headway. This means that drivers extend the gap to the vehicles in front for a better anticipation of the traffic which can improve both safety and eco-friendly predictive driving. However, this effect can only be shown for two out of four different systems tested.

8.15 Hypothesis 22: Using an ecoDriver system, there will be shorter distances to vehicles at crest

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
22 THW Situations	Average time headway at crest	Urban	-0.61 (N.S.)	-0.68 (N.S.)	-0.93 (N.S.)	-	-	-
		Rural	0.68 (N.S.)	4.76 (N.S.)	13.69 (N.S.)	-	-	-
		Motorway	-	-	-	-	-	-
		All road types	0.33 (N.S.)	1.5 (N.S.)	1.99 (N.S.)	-1.38 (N.S.)	-	-

Before crests, no significant effects for changes in average THW in treatment compared to baseline driving could be observed. When analysing the four different subsets of ecoDriver systems separately, also no significant differences in THW were found. An increase of the average THW implies an increase of the average distance headway. This means that drivers extend the gap to the vehicles in front for a better anticipation of the traffic which can improve both safety and eco-friendly predictive driving. However, this effect cannot be shown for any of the tested systems within the range of crests.

8.16 Hypothesis 23: Using an ecoDriver system, there will be shorter distances to vehicles before speed limit changes

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
23 THW Situations	Average time headway before speed limit changes	Urban	7.19	13.95	16.80	5.59 (N.S.)	-	-
		Rural	3.79 (N.S.)	3.42 (N.S.)	3.39 (N.S.)	-0.36 (N.S.)	-	-
		Motorway	11.36 (N.S.)	12.24 (N.S.)	17.8 (N.S.)	-	-	-
		All road types	5.43	8.22	9.70	1.33 (N.S.)		

Before speed limit changes, the average THW increases in the treatment condition compared to baseline driving which implies an increase of distance to front vehicles. This effect can be observed on all road types. When analysing the four different subsets of ecoDriver systems separately, significant differences between baseline and treatment condition could only be shown for embedded systems and the FeDS. For the embedded system, the analysis reveals that the effect is largest on motorways. No significant differences in THW were observed for the ecoDriver App and the haptic vs. non-haptic treatment conditions. An increase of the average THW implies an increase of the average distance headway. This means that drivers extend the gap to the vehicles in front for a better anticipation of the traffic which can improve both safety and eco-friendly predictive driving. However, this effect can only be shown for two out of four different systems tested. In contrast to other situations such as intersections or the overall analysis of the data, the greatest effect before speed limit changes can be observed on urban roads (for the FeDS).

8.17 Hypothesis 24: Using an ecoDriver system, there will be more red or amber light violations

Hypotheses regarding red or amber light violations could not be analysed because they were not registered with the observer protocol. The observer protocol was used in the controlled studies and therefore, the driver was accompanied by an observer and hence they were perhaps less likely to pass on an amber or red traffic light.

8.18 Hypothesis 25: Using an ecoDriver system, there will be fewer overtakings

The number of overtakings was compared between baseline and ecoDriver system use. The average of overtakings for baseline situations and average number of overtakings for experimental phases were calculated. The hypothesis was not supported in any of the system comparisons (baseline vs treatment, embedded, FeDS, ecoDriver App and haptic situation). In fact, the medians are almost zero in all the cases. This situation seems similar to the previous hypothesis - maybe when the driver is being observed they are more cautious and do not risk overtaking. In naturalistic studies it may be possible to observe this type of behaviour.

8.19 Hypothesis 26: Using an ecoDriver system, there will be less overspeeding

Knowing that using only information from the observer protocol was insufficient to draw any firm conclusions, it was decided to add a new hypothesis regarding speeding (here defined as driving above the posted speed limit). Using information from the datalogger in combination with the speed limit, speeding was calculated for controlled and naturalistic studies. In the case of naturalistic studies, only comparisons Type A and Type D could be performed. It was confirmed that there were statistically significant less speed limit exceedances when using ecoDriver systems when comparing baseline with treatment, baseline embedded with embedded and baseline FeDS vs FeDS in controlled studies. Differences were not statistically significant for ecoDriver App and haptic comparisons.

In the naturalistic studies, two analyses could be run involving a comparison between baseline and treatment (Type A) and comparison between ecoDriver App baseline and ecoDriver App. Only the first comparison was statistically significant and, once more, the number of speed exceedances was higher in baseline condition vs treatment condition. In the second comparison, the medians were around 4 speed exceedances and although it was higher in ecoDriver App condition the differences were not statistically significant.

8.20 Hypothesis 27: Using an ecoDriver system, the average rpm when shifting up will be reduced

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
27 Golden rules	Average rpm when shifting gear up	Urban	-0.73 (N.S.)	5.63	6.68	7.34	3.76 (N.S.)	3.85
		Rural	11.44	9.97	12.23	7.43	1.35 (N.S.)	8.29
		Motorway	3.19	3.42	3.32	-	-	2.19
		All road types	7.09	7.14	7.90	8.03	1.92 (N.S.)	2.97

The first golden rule of eco-driving advises the driver to *Shift up as soon as possible.* The average rpm when shifting up reflects the application of this rule. A reduction of this PI is expected if ecoDriver systems succeed in generating a green driving behaviour as defined by professionals.

On average, all systems together have significant and positive effect in decreasing the average rpm when shifting gear up. This effect is stronger on rural roads, less salient on motorway and not significant on urban roads. The ecoDriver systems positive impact on average rpm when shifting gear up is significant when driving on rural and motorway compared to urban. Compared to their baseline, the embedded systems provide significant reduction of the average rpm when shifting gear up in all road conditions. As already stated, the effect is larger for rural roads. Compared to its own baseline, the FeDS system present the same picture as the larger category of embedded system (FeDS is an embedded system). The main effect is significant, with a reduction of the average rpm when shifting gear up, up to 12% in rural conditions.

The ecoDriver App is significantly reducing globally the average rpm when shifting gear up. This reduction is significant for both urban and rural roads (no data for motorway with the App). Using a haptic pedal additional to an ecoDriver non-haptic system does not significantly decrease the average rpm when shifting gear up. There is no additional improvement for this PI with a haptic pedal.

The observed effects of ecoDriver systems on controlled roads are similar for the naturalistic data set. The greater reduction of Average rpm when shifting gear up is observed on rural roads, while reduction is smaller on urban conditions and for motorways. Effects for naturalistic data are in line with the controlled ones. Thus non-embedded system (ecoDriver App) seems to perform well in helping the driver to change gear earlier.

8.21 Hypothesis 28: Using an ecoDriver system, the weighted average engine rpm will be decreased

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					**Naturalistic**
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
28 Golden rules	weighted average engine rpm	Urban	2.48	9.12	9.39	7.70	-0.99 (N.S.)	7.13
		Rural	14.43	13.95	14.20	6.00	0.89 (N.S.)	9.12
		Motorway	4.15	4.41	3.72	-	-	2.24 (N.S.)
		All road types	9.64	10.24	9.46	7.03	0.42 (N.S.)	5.00

The second golden rule of eco-driving advises the driver to *maintain a steady speed by the mean of using the highest gear possible and drive with low engine RPM.* This driving behaviour can be measured using a specific PI corresponding to a weighted average of the engine rpm within each gear. The lower this PI, the lower is the average rpm and the more eco-friendly the driving is. The weighted average engine rpm is a PI without unit.

All systems together, there is significant decrease of the weighted average engine rpm compared to baseline. The weighted average engine rpm is significantly lower on urban roads than on rural or motorways, denoting globally lower rpm associated to low gears. On average the systems are significantly more effective on rural roads.

Embedded systems also present significant positive effects (reduction of the PI, showing lower rpm) on all road types. The effect is slightly more pronounced on rural roads. Embedded systems show better performances on urban roads compared to the average of all systems. The FeDS system performances are similar to the embedded systems in general. The global impact is significant, and it is also significant on every road types. The ecoDriver App is not evaluated on motorways. The impact of the App on urban and rural road types is of similar size and significant (around 7% reductions). The haptic versions of the systems are not providing any additional positive effects compared to not haptic ecoDriver systems.

The naturalistic data present more variability than the controlled datasets. Despite this, we observe significant impact of the systems. The impact is significant for both urban and rural roads, with a greater effect for rural. The impact of the systems are still positive (reduction of the weighted average rpm) in real usage condition and comparable to their performances in controlled studies (Type D comparison).

8.22 Hypothesis 29: Using an ecoDriver system, the variability of speed profiles will be decreased

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
29 Golden rules	Positive kinetic energy	Urban	6.25	3.23	3.17	1.45 (N.S.)	0 (N.S.)	1.56 (N.S.)
		Rural	1.72	5.00	3.51	0 (N.S.)	1.54 (N.S.)	0 (N.S.)
		Motorway	0 (N.S.)	0 (N.S.)	0 (N.S.)	-	-	0 (N.S.)
		All road types	3.39	3.39	1.79	0 (N.S.)	1.52 (N.S.)	1.69

The third rule of eco-driving advises the driver to *anticipate traffic flow by looking ahead as far as possible and anticipate the surrounding traffic.* As anticipating while driving induces smoother speed profiles, we chose to monitor the changes due to the application of this rule by the positive kinetic energy (PKE). The lower the PKE, the smoother the speed profile. This PI is highly correlated with fuel consumption.

The ecoDriver systems are globally reducing the PKE which is the sign of smoother speed profiles. This reduction is higher on urban areas than on rural. There is no significant change for motorway conditions. Embedded systems present the same picture than the overall baseline vs treatment comparison. There is a global significant decrease, due to urban and rural conditions, while there is no effect on motorways. The FeDS system, which is part of the embedded systems, presents the same pattern. The decrease in PKE is a bit smaller than for the average of the embedded systems, but still significant. There is no impact on motorways. The ecoDriver App does not present significant differences in PKE from baseline. This is likely due to the absence of advice about instant green speed in the App. The haptic version of the systems does not present significant differences in PKE with the non-haptic systems.

For the naturalistic data set, the global picture is less significant. The global effect of systems is still significant and positive, but it couldn't be detected per road type. It seems real conditions tend to lower the usage of this driving technique.

8.23 Hypothesis 30: Using an ecoDriver system, the use of the engine brake will be improved

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
30 Golden rules	Percentage of driving time with engine brake	Urban	-2.89 (N.S.)	1 (N.S.)	2.15 (N.S.)	1.96 (N.S.)	-2.86 (N.S.)	-0.71 (N.S.)
		Rural	5.13	1.48 (N.S.)	5.11	6.38	-5.61 (N.S.)	3.73 (N.S.)
		Motorway	1.89 (N.S.)	2.24 (N.S.)	2.15 (N.S.)	-	-	-4.73
		All road types	1.83	1.17 (N.S.)	3.29	4.90	-5.11	-0.54 (N.S.)

The fourth golden rule advises the driver to *decelerate smoothly by releasing the accelerator in time, leaving the car in gear.* The usage of this driving technique can measured with the percentage of driving time with engine brake. This PI needs to increase for a more ecofriendly way to drive.

All systems together, a significant improvement is only observed on rural roads, for which percentage of driving time with engine brake is increased by 5%. Neither urban roads nor motorways present any significant effect. The embedded systems category provides significant and positive changes only for rural roads. As a part of the embedded systems, the FeDS provide the same picture: A significant and positive effect on rural roads, and no effect on other road types. The ecoDriver App (no data on motorways) is also presenting a positive and significant change for rural roads. There is no effect on urban roads. Considering haptic version of systems, the main effect is globally significant and negative. It could be that the haptic pedal does not make engine braking easy, or it could be a bigger representation of the rural roads in our sample. Moreover, no significant change is observed across road types when changing from an ecoDriver non-haptic system, to an ecoDriver haptic one.

For the naturalistic experiment, the main effect is not significant, but when looking into the details, there is a small negative effect (reduction of percentage of driving time with engine brake) observed on motorways. Other eco-friendly driving techniques may be preferred by natural drivers on motorways, or it could be that a better anticipation of the traffic may reduce the needs for a braking.

8.24 Hypothesis 31: Using an ecoDriver system, the acceleration distribution will change

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	(App) Type A
31 Accel Decel	95th percentile positive acceleration	Urban	13.12	8.54	5.17	2.11 (N.S.)	-4.38 (N.S.)	4.77
		Rural	4.43	13.21	8.42	1.61 (N.S.)	3.59 (N.S.)	3.06 (N.S.)
		Motorway	-1.2 (N.S.)	0 (N.S.)	5.8 (N.S.)	-	-	7.44 (N.S.)
		All road types	8.10	9.81	6.57	1.12 (N.S.)	-0.09 (N.S.)	4.57

The ecoDriver systems as a whole change the acceleration distribution, i.e. it reduces 95th percentile acceleration, for urban and rural roads. This reduction is not present for motorway data. Focusing on the embedded or FeDS ecoDriver system shows a similar reduction of 95th percentile acceleration for urban and rural roads, but not for motorways. The ecoDriver App is not found to have a significant effect on this hypothesis' performance indicator. Furthermore, in this data no significant difference between haptic and non-haptic systems is apparent in changing the acceleration distribution. For naturalistic drives there is a considerable (19.5%) reduction of 95th percentile acceleration on rural roads. Conversely, on rural roads and motorway increased (respectively 6.5% and 14.8%) 95th percentile acceleration is found. Note that in absolute terms this reduction on urban roads is double or more compared to the increase in rural and motorway data. In general, the lower 95th percentile acceleration translates into less aggressive driving with lower peak-accelerations.

8.25 Hypothesis 32: Using an ecoDriver system, the deceleration distribution will change

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
32 Accel Decel	5th percentile negative acceleration	Urban	11.34	5.11	6.45	0.65 (N.S.)	0 (N.S.)	3.88
		Rural	3.64	14.65	7.14	-1.54 (N.S.)	4.65 (N.S.)	3.28 (N.S.)
		Motorway	0 (N.S.)	0 (N.S.)	3.7 (N.S.)	-	-	7.38
		All road types	7.46	9.02	5.80	-1.05 (N.S.)	1.92 (N.S.)	4.31

In controlled drives the ecoDriver system leads to reduction in 5th percentile deceleration on urban and rural roads of 10.1% and 7.4% respectively. This effect can also be seen in the subset of embedded and FeDS ecoDriver systems, but is not present in the data on the ecoDriver App. Furthermore, no significant difference between non-haptic and haptic systems in reducing 5th percentile deceleration was found. In naturalistic drives the reduction of 5th percentile negative acceleration on urban roads is even more pronounced with 17%. On motorways during naturalistic drives, this performance indicator was increased. The lack of effect during controlled drives on motorways is most likely due to the vastly different driving environment compared to urban and rural roads. Stopping and accelerating occurs especially in urban conditions, where the distribution of (negative) acceleration is of most interest since there is most to gain in terms of driving behaviour. Less intense deceleration is both safer and more fuel efficient, and is beneficial to traffic flow.

8.26 Hypothesis 33: Using an ecoDriver system, acceleration after being stationary will be less aggressive

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
33 Accel Decel	maximum acceleration after stationnary	Urban	2.22	2.94	0.7 (N.S.)	1.77	-4.21 (N.S.)	-
		Rural	-	-	-	-	-	-
		Motorway	-	-	-	-	-	-
		All road types	-	-	-	-	-	-

The ecoDriver system reduces maximum acceleration after standstill. For the ecoDriver system in controlled drives, maximum acceleration was reduced by 2.2%. Note that since this hypothesis is concerned with acceleration after standstill, only urban roads are considered.

8.27 Hypothesis 34: Using an ecoDriver system, the acceleration distribution will change before intersections

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Treatment (all systems) Type A**	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
34 Accel Decel Situation	95th percentile of the negative acceleration before intersections	Urban	4.95	4.74	3.94	-0.09 (N.S.)	3.50	-
		Rural	-0.94	4.38	3.64	-1.42 (N.S.)	1.01 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.12	4.59	3.84	-	-	-

The use of the ecoDriver systems significantly reduces the deceleration before intersections in both urban and rural driving environments. On urban roads, the effect is bigger than on rural roads. Between baseline and treatment of all the systems, the back transformed model-based estimates for extreme deceleration are reduced from -0.85 m/s^2 to -0.77 m/s^2 for urban driving and from -0.71 m/s^2 to -0.66

m/s^2 for rural driving. Similar values are found for the embedded systems and the FeDS. The Android App has similar results on urban roads, but the significance condition is slightly violated. On rural roads, the Android App has no significant effect. The haptic systems have no significant effect compared to the non-haptic system on rural roads either. On urban roads, however, the back transformed estimates for extreme deceleration are further reduced from -0.71 m/s^2 to -0.66 m/s^2

8.28 Hypothesis 35: Using an ecoDriver system, the acceleration distribution will change before zebra crossings

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	**PI abbreviated**	**Road type**	**Controlled**					**Naturalistic**
			Treatment (all systems) Type A	**Embedded Type B**	**FeDS Type C**	**App Type D**	**Haptic Type E**	**App Type A**
35 Accel Decel Situation	95th percentile of the negative acceleration before zebra crossings	Urban	2.39	2.61 (N.S.)	4.19 (N.S.)	0.76 (N.S.)	5.25 (N.S.)	-
		Rural	-11.03	6.51 (N.S.)	15.75	-7.55 (N.S.)	-2.84 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	1.53	3.07	5.72	0.56 (N.S.)	4.30	-

The use of the ecoDriver systems reduces significantly the extreme deceleration values before zebra crossings in urban driving environments. The back transformed extreme deceleration model based estimates are reduced from -0.55 m/s^2 to -0.52 m/s^2 for urban driving. In rural environments the difference however, is significantly negative. The reason is unclear because this result merge the impact from both OEM systems, the FeDS, and the App. It is clear that the FeDS have a positive effect on rural roads (+15.75%) in contrast to all ecoDriver systems, while the effect is negative for the App. The effect of embedded systems being smaller than the FeDS effect alone, it could be that merging the FeDS and the App together with other OEM systems may lead to a global negative effect.

The expected average differences are not significant for the App baseline vs. App condition and are also not significant for the non-haptic vs. haptic condition in both urban and rural environments. This implies there is significant evidence that the usage of an ecoDriver system can have an influence on the actual driving behaviour before the event of zebra crossings. However, as this effect is only significant for some configurations, there is still room for improvement, especially for the App in urban and rural environments, but also for the FeDS condition in urban environments.

8.29 Hypothesis 36: Using an ecoDriver system, the acceleration distribution will change before speed bumps

Effect sizes in percentages (differences in % from relevant baseline)

Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
36 Accel Decel Situation	95th percentile of the negative acceleration before speed bumps	Urban	6.43	10.95	16.96	4.49	2.06 (N.S.)	-
		Rural	12.37	12.82	12.89	11.98	-	-
		Motorway	-	-	-	-	-	-
		All road types	7.02	11.06	15.40	4.91	-	-

The use of the ecoDriver systems reduces significantly the extreme deceleration values before speed bumps. The back transformed extreme deceleration model based estimates are reduced from -1.04 m/s^2 to -0.76 m/s^2 for rural driving. There is also a reduction of the expected average extreme deceleration for the hypotheses ecoDriver system, embedded systems, FeDS, and App system compared to their respective baselines. Only the haptic condition has a stronger expected average extreme deceleration compared to the non-haptic condition. The expected average differences are significant for the baseline vs. treatment condition, embedded baseline vs. embedded condition, and FeDS baseline vs. FeDS. The expected average differences are not significant for the non-haptic vs. haptic condition and for the App baseline vs. App condition. This implies there is significant evidence that the usage of an ecoDriver system has an influence on the actual driving behaviour before the event of speed bumps. Furthermore, assuming that less deceleration corresponds to longer coasting and hence the predictive awareness is increased before the event of speed bumps. Compared to other events i.e. sharp curves and zebra crossings the difference of the model based average estimates is much stronger. Furthermore, in the evaluation data set, only data for urban driving environments were available.

8.30 Hypothesis 37: Using an ecoDriver system, the acceleration distribution will change before sharp curves

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
37 Accel Decel Situation	95th percentile of the negative acceleration before sharp curves	Urban	3.44	4.09	1.96 (N.S.)	-0.7 (N.S.)	8.24	-
		Rural	4.25	5.41	4.13	0.78 (N.S.)	1.27 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.88	4.80	3.28	0.18 (N.S.)	4.51	-

The use of the ecoDriver systems reduces significantly the extreme deceleration values before sharp curves. The back transformed extreme deceleration model based estimates are reduced from -1.14 m/s^2 to -1.06 m/s^2 for urban driving. There is also a reduction of the expected average extreme deceleration for all five hypotheses, i.e. for all ecoDriver system, embedded systems, FeDS, App, and haptic system compared to their respective baselines. Only the App has a stronger expected average extreme deceleration in rural driving environment, compared to the baseline. The expected average differences are significant for the baseline vs. treatment condition, embedded baseline vs. embedded condition, FeDS baseline vs. FeDS condition (only in rural environments), and non-haptic vs. haptic condition (only in urban environments). The back transformed extreme deceleration model based estimates are reduced from -0.88 m/s^2 to -0.74 m/s^2 for the haptic condition compared to the non-haptic condition in urban driving environments. The expected average differences are not significant for the FeDS baseline vs. FeDS condition (in urban environments), non-haptic vs. haptic condition (in rural environments), and especially for the App baseline vs. App condition.

This implies there is significant evidence that the usage of an ecoDriver system has an influence on the actual driving behaviour before the event of sharp curves. Furthermore, assuming that less deceleration corresponds to longer coasting and hence the predictive awareness is increased before the event of sharp curves. Presumably, the deceleration reduction has the largest effect when using an embedded system, which can be further strengthened if a haptic accelerator pedal is used in urban environments. In general, the model based average estimated extreme deceleration values before sharp curves are much stronger in urban areas compared to rural environments.

8.31 Hypothesis 38: Using an ecoDriver system, the acceleration distribution will change at crests

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
38 Accel Decel Situation	95th percentile of the negative acceleration at crests	Urban	0.65 (N.S.)	0.66 (N.S.)	0.59 (N.S.)	-	-	-
		Rural	4.18 (N.S.)	5.62	5.48 (N.S.)	-1.57 (N.S.)	-3.75 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.44	4.31	3.89	-	-	-

Probably due to the smaller number of samples compared to the sharp curve approach, most analyses of the effect of the ecoDriver system on deceleration at crests do not show statistically significant results. Only the effect of embedded systems at crests on rural roads is significant. In that comparison, the model-based average estimate of the 95th percentile of negative acceleration changes from 0.89 to 0.84 by using the ecoDriver system. Transformed back to deceleration, this is a change from -0.79 to -0.71 m/s². The magnitude of this effect is similar to the one for the significant effects before sharp curves.

The effects of all systems (treatment in Type A comparison) and the FeDS have a similar magnitude for rural roads but the significance condition is violated slightly. For urban roads, the effect is almost 0 and not significant at all in all the comparisons. The Android App shows no effect either, as in the case before sharp curves. The numbers indicate that the haptic system might further reduce the 95th percentile of negative acceleration at crests on rural roads. Due to the small number of observations, however, the change is not statistically significant.

The results suggest that the ecoDriver system does have a positive effect on the driving behaviour at crests, lowering deceleration, although the results do not have such strong significance values as other comparisons. Note that the change of the 95th percentile of negative acceleration at crests normally concerns the approach to the crest since the part after the crest mostly has positive acceleration.

8.32 Hypothesis 39: Using an ecoDriver system, the acceleration distribution will change before speed limit changes

Effect sizes in percentages (differences in % from relevant baseline)								
			Controlled					Naturalistic
Hyp. Number & cat.	PI abbreviated	Road type	Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
39 Accel Decel Situation	95th percentile of the negative acceleration before speed limit changes	Urban	1.42 (N.S.)	2.57 (N.S.)	2.87 (N.S.)	-2.01 (N.S.)	8.24	-
		Rural	4.11	4.94	1.69 (N.S.)	0.21 (N.S.)	1.27 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	2.96	3.83	2.09 (N.S.)	-0.4 (N.S.)	4.51	-

The use of the ecoDriver systems reduces significantly the extreme deceleration values before speed limit changes to a lower speed limit in rural environments. The back transformed extreme deceleration model based estimates are reduced from -0.79 m/s^2 to -0.72 m/s^2 for rural driving. There is also a significant reduction of the expected average extreme deceleration for the hypothesis of embedded systems compared to their baselines. The differences of the model based average estimates are not significant for all other conditions, i.e. FeDS vs. FeDS baseline, App vs. App baseline, and haptic vs. non-haptic. Also there is no significant difference in all conditions for urban driving environments.

This implies there is significant evidence that the usage of an ecoDriver system has an influence on the actual driving behaviour before the event of speed limit changes in rural driving environments. Furthermore, assuming that less deceleration corresponds to longer coasting and hence the predictive awareness is increased before the event of speed limit changes. For this hypothesis the condition embedded is the only one, which significantly decreases the extreme deceleration values before speed limit changes.

8.33 Summary of results — driver speed

SPEED

- Using an ecoDriver system the average velocity when cruising will be lower
- Using an ecoDriver system the average free velocity will be lower
- Using an ecoDriver system, speed will change when driving before locations where a low speed is recommended by the system

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	(App) Type A
9 Speed	5th percentile negative acceleration	Urban	-2.79	3.30	4.76	-8.86 (N.S.)	3.63	3.28
		Rural	4.04	1.82	1.71 (N.S.)	2.17 (N.S.)	-0.95 (N.S.)	0.03 (N.S.)
		Motorway	3.42	3.32	3.50	-	-	1.25
		All road types	2.39	2.53	2.95	-	0.74 (N.S.)	1.24
10 Speed	maximum acceleration after stationnary	Urban	3.07 (N.S.)	10.61	9.83	0.45 (N.S.)	-11.87 (N.S.)	-
		Rural	3.55	0.37 (N.S.)	0.37 (N.S.)	1.31 (N.S.)	-0.05 (N.S.)	-
		Motorway	0.57 (N.S.)	0.67 (N.S.)	0.62 (N.S.)	-	-	-
		All road types	2.97	4.06	2.78	1.18 (N.S.)	4.84 (N.S.)	-
11 Speed Situations	95th percentile of the negative acceleration before intersections	Urban	-3.14	-0.13 (N.S.)	2.76	-1.4 (N.S.)	1.1 (N.S.)	-
		Rural	5.60	3.47	1.82	1.78	1.22 (N.S.)	-
		Motorway	5.08	5.01	2.57	-	-	-
		All road types	1.32	1.66	1.58	-0.61 (N.S.)	1.00	-
12 Speed Situations	95th percentile of the negative acceleration before zebra crossings	Urban	-0.99 (N.S.)	2.33	4.18	0.49 (N.S.)	0.07 (N.S.)	-
		Rural	13.13	2.43 (N.S.)	3.47 (N.S.)	3.18	-1.83 (N.S.)	-
		Motorway	7.6 (N.S.)	7.58 (N.S.)	7.19 (N.S.)	-	-	-
		All road types	1.29	2.22	3.53	0.59 (N.S.)	-0.08 (N.S.)	-
13 Speed Situations	95th percentile of the negative acceleration before speed bumps	Urban	1.1 (N.S.)	2.26 (N.S.)	1.32 (N.S.)	0.6 (N.S.)	-6.61 (N.S.)	-
		Rural	0.99 (N.S.)	1.65 (N.S.)	1.88 (N.S.)	-0.12 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	0.77 (N.S.)	1.46 (N.S.)	0.37 (N.S.)	-0.12 (N.S.)	-6.61 (N.S.)	-
14 Speed Situations	95th percentile of the negative acceleration before sharp curves	Urban	-2.38 (N.S.)	1.35 (N.S.)	1.85 (N.S.)	3.26 (N.S.)	4.96	-
		Rural	3.72	2.45	3.40	1.35 (N.S.)	-1.46 (N.S.)	-
		Motorway	0.44 (N.S.)	0.22 (N.S.)	5.1 (N.S.)	-	-	-
		All road types	1.33	1.83	2.24	-0.79 (N.S.)	1.18 (N.S.)	-

15 Speed Situations	95th percentile of the negative acceleration at crests	Urban	0.87 (N.S.)	0.94 (N.S.)	0.69 (N.S.)	2.25 (N.S.)	2.5 (N.S.)	-
		Rural	1.25 (N.S.)	1.08 (N.S.)	0.34 (N.S.)	2.16	1.18 (N.S.)	-
		Motorway	-2.66 (N.S.)	-2.65 (N.S.)	-2.62 (N.S.)	-	-	-
		All road types	1.68	1.59 (N.S.)	1.29 (N.S.)	2.21	1.06 (N.S.)	-
16 Speed Situations	95th percentile of the negative acceleration before speed limit changes	Urban	1.41 (N.S.)	2.54 (N.S.)	4.2 (N.S.)	3.08 (N.S.)	1.14 (N.S.)	-
		Rural	2.30	2.36	2.35 (N.S.)	0.74 (N.S.)	-2.67 (N.S.)	-
		Motorway	6.42	6.31	4.24	-	-	-
		All road types	2.56	2.98	3.06	1.45 (N.S.)	-1.23 (N.S.)	-

8.33.1 Results combining all systems

On average, the controlled drives with the systems show a reduction in speed when cruising by 3.4% (motorway) to 4% (rural), despite the negative impact observed on urban roads (an increase of 2.8%). This negative result is likely to be impacted by the increase of speed observed with the App on urban, although it is not significant taken alone. The naturalistic data show an even greater reduction in cruising speed, by up to 8.5%. Average speed when free driving is reduced by about 3% for the controlled studies, without evidence of the same effect for naturalistic data, perhaps because conditions varied more in the naturalistic drives. There is clear evidence of a speed reduction in advance of specific infrastructures studied. Speed reduced in advance of intersections and speed limit decreases in rural and motorway conditions, and in advance of sharp curves in rural conditions only. Such effects are closely linked with some of the system features (e.g., advice to slow down when approaching a sharp curve). However, there was some evidence of a speed reduction on the approach to zebra crossings in rural conditions, despite the system not providing advice for these specific infrastructures. This suggests that the systems may have more general impacts on green driving behaviour.

8.33.2 Results across road types

Reduction of speed is observed mostly on rural roads and motorway for the controlled drives, while the larger reduction (8.5%) is observed for the naturalistic data on urban roads. Potential benefits exist for both rural and urban road types when systems alert for infrastructure constraints.

8.33.3 Results across system categories

The embedded systems provide strong evidence of a cruising speed reduction of 1.5% to 3.5% in all conditions, while the App does not show any significant effect. The haptic systems obtained an *additional* 3.6% reduction. It is very promising to show a reduction of cruising speed in real conditions by up to 8.5% on urban roads. Free driving speed is also reduced by around 10% in urban areas with the embedded systems. In summary, a reduction of speed (cruising or free) is induced by the embedded systems (up to 10%), but also by the nomadic systems (ecoDriver App and TomTom, by up to 8.5%) when used in real conditions. The reduction of speed before specific infrastructure elements is closely linked to the way they are treated and displayed by the system. Around events, the embedded systems showed speed reductions of up to 6.3%, with the largest effects observed before a speed limit change and on the approach to intersections. High safety benefits can be expected in reducing crash severity as a result of using an ecoDriver system.

8.34 Summary of results — time headway

THW DISTANCE / SITUATIONS

- Using an ecoDriver system, the time headway distribution to leading vehicle will change
- Using an ecoDriver system, there will be shorter distances to vehicles before safety critical locations

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
17 THW Situations	5th percentile negative acceleration	Urban	6.50	11.15	12.23	3.97 (N.S.)	-	-
		Rural	5.86	5.65 (N.S.)	4.71 (N.S.)	-1.88 (N.S.)	-	-
		Motorway	8.56	9.17	12.36	-	-	-
		All road types	6.29	9.06	10.24	-0.33 (N.S.)	4.45 (N.S.)	-
18 THW Situations	maximum acceleration after stationnary	Urban	8.10	12.93	13.87	3.67 (N.S.)	-	-
		Rural	2.6 (N.S.)	4.58	5.45 (N.S.)	-7.63 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	5.63	9.57	10.36	-1 (N.S.)	15.23	-
19 THW Situations	95th percentile of the negative acceleration before intersections	Urban	-1.42 (N.S.)	2.87 (N.S.)	1.95 (N.S.)	-2.11 (N.S.)	-	-
		Rural	1.67 (N.S.)	-3.1 (N.S.)	-3.54 (N.S.)	4.45 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	-1.13 (N.S.)	1.42 (N.S.)	0.32 (N.S.)	-1.74 (N.S.)	11.64 (N.S.)	-
20 THW Situations	95th percentile of the negative acceleration before zebra crossings	Urban	6.77 (N.S.)	8.12 (N.S.)	8.12 (N.S.)	6.47 (N.S.)	-	-
		Rural	0.32 (N.S.)	-6.8 (N.S.)	-6.8 (N.S.)	8.06 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	4.49 (N.S.)	0.69 (N.S.)	0.69 (N.S.)	6.33 (N.S.)	-	-
21 THW Situations	95th percentile of the negative acceleration before speed bumps	Urban	4.62 (N.S.)	16.54	22.27	0.56 (N.S.)	-	-
		Rural	7.87 (N.S.)	3.73 (N.S.)	2.73 (N.S.)	8.37 (N.S.)	-	-
		Motorway	-	-	-	-	-	-
		All road types	4.73 (N.S.)	8.36	8.68	1.32 (N.S.)	-	-

22 THW Situations	95th percentile of the negative acceleration before sharp curves	Urban	-0.61 (N.S.)	-0.68 (N.S.)	-0.93 (N.S.)	-	-	-
		Rural	0.68 (N.S.)	4.76 (N.S.)	13.69 (N.S.)	-	-	-
		Motorway	-	-	-	-	-	-
		All road types	0.33 (N.S.)	1.5 (N.S.)	1.99 (N.S.)	-1.38 (N.S.)	-	-
23 THW Situations	95th percentile of the negative acceleration at crests	Urban	7.19	13.95	16.80	5.59 (N.S.)	-	-
		Rural	3.79 (N.S.)	3.42 (N.S.)	3.39 (N.S.)	-0.36 (N.S.)	-	-
		Motorway	11.36 (N.S.)	12.24 (N.S.)	17.8 (N.S.)	-	-	-
		All road types	5.43	8.22	9.70	1.33 (N.S.)	-	-
27 Golden rules	95th percentile of the negative acceleration before speed limit changes	Urban	-0.73 (N.S.)	5.63	6.68	7.34	3.76 (N.S.)	3.85
		Rural	11.44	9.97	12.23	7.43	1.35 (N.S.)	8.29
		Motorway	3.19	3.42	3.32	-	-	2.19
		All road types	7.09	7.14	7.90	8.03	1.92 (N.S.)	2.97

8.34.1 Results combining all systems

On average, all systems together increased time headway by 5% to 9%. The systems had no impact before zebra crossings, speed bumps and crests, but time headway increased by up to 8.1% before intersections. The systems also increased time headway before speed limit changes on all road types.

8.34.2 Results across road types

Average time headway increased globally for every road type with stronger effects in urban conditions. Overall effects on time headway were particularly strong for motorways for the FeDS. Before intersections, haptic systems show the greatest effects on all road types (15.2 %).

8.34.3 Results across system categories

As could have been predicted, the ecoDriver App and the haptic systems do not provide benefits on THW as they are not intended to deal with this external information. Benefits came only from the embedded systems and were also for the FeDS itself. In summary, systems that had and used radar information (embedded), can have a positive impact in increasing THW by up to 22.3%. Significant impacts were observed before intersections (13.9 %), sharp curves (22.3 %), and speed limit changes (16.8 %).

8.35 Summary of results — driver behaviour in events

EVENTS

- Using an ecoDriver system, there will be more red or amber light violations
- Using an ecoDriver system, there will be fewer overtakings

Events such as red or amber light violations during the controlled trials proved very difficult to observe in a reliable way. Overtaking was observed at an identical rate, while fewer instances of speeding were observed when using embedded systems.

8.36 Summary of results — the four golden rules

4 GOLDEN RULES

- Using an ecoDriver system, the average rpm when shifting up will be reduced
- Using an ecoDriver system, the weighted average engine rpm will be decreased
- Using an ecoDriver system, the variability of speed profiles will be decreased
- Using an ecoDriver system, the use of the engine brake will be improved

Effect sizes in percentages (differences in % from relevant baseline)

Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
27 Golden rules	Average rpm when shifting gear up	Urban	-0.73 (N.S.)	5.63	6.68	7.34	3.76 (N.S.)	3.85
		Rural	11.44	9.97	12.23	7.43	1.35 (N.S.)	8.29
		Motorway	3.19	3.42	3.32	-	-	2.19
		All road types	7.09	7.14	7.90	8.03	1.92 (N.S.)	2.97
28 Golden rules	weighted average engine rpm	Urban	2.48	9.12	9.39	7.70	-0.99 (N.S.)	7.13
		Rural	14.43	13.95	14.20	6.00	0.89 (N.S.)	9.12
		Motorway	4.15	4.41	3.72	-	-	2.24 (N.S.)
		All road types	9.64	10.24	9.46	7.03	0.42 (N.S.)	5.00
29 Golden rules	Positive kinetic energy	Urban	6.25	3.23	3.17	1.45 (N.S.)	0 (N.S.)	1.56 (N.S.)
		Rural	1.72	5.00	3.51	0 (N.S.)	1.54 (N.S.)	0 (N.S.)
		Motorway	0 (N.S.)	0 (N.S.)	0 (N.S.)	-	-	0 (N.S.)
		All road types	3.39	3.39	1.79	0 (N.S.)	1.52 (N.S.)	1.69
30 Golden rules	Percentage of driving time with engine brake	Urban	-2.89 (N.S.)	1 (N.S.)	2.15 (N.S.)	1.96 (N.S.)	-2.86 (N.S.)	-0.71 (N.S.)
		Rural	5.13	1.48 (N.S.)	5.11	6.38	-5.61 (N.S.)	3.73 (N.S.)
		Motorway	1.89 (N.S.)	2.24 (N.S.)	2.15 (N.S.)	-	-	-4.73
		All road types	1.83	1.17 (N.S.)	3.29	4.90	-5.11	-0.54 (N.S.)

8.36.1 Results combining all systems

For the controlled drives, all systems had a positive impact on the different rules of eco-driving, except the haptic variant which did not show any improvement. The use of the engine brake (rule 4) improved only on rural roads. Results are more variable for the naturalistic drives, but still overall positive for the first two rules (1: average rpm when shifting up, 2: weighted average engine rpm). The use of the engine brake (rule 4) seems to be reduced on motorways while there was a global significant but small change for the flatness of the speed profiles (rule 3).

8.36.2 Results across road types

Within the controlled drives, positive effects of the systems are observed on every road type, with some exceptions due to the rule itself (speed profiles, rule 3, are already very flat on motorways and a change is therefore difficult to observe). For the naturalistic drives, benefits comes from rule 1 and 2 only. No significant change is observed in the flatness of the speed profiles (rule 4), and engine brake is reduced with the system on motorways.

8.36.3 Results across system categories

The haptic version of the ecoDriver system does not induce any changes with respect to the golden rules. The FeDS system performed very well compared to the embedded category overall. The embedded systems, including FeDS succeeded in generating a driving behaviour compliant with the golden rules of eco-driving. The ecoDriver App also generated green driving behaviour, but less saliently than the embedded systems, but did not affect the speed profile (rule 3). The use of the engine brake increased with both embedded and the App, but only for rural roads. Nomadic systems tested under naturalistic driving conditions (the App) provide positive effects for the gear shifting behaviour (rule 1 and 2), although they are not always effective, and even provide some disappointing results: reduction of engine brake usage on motorways. In summary, the ecoDriver systems succeed in generating a driving behaviour compliant with the golden rules.

8.37 Summary of results — acceleration and deceleration

ACCEL DECEL / SITUATIONS

- Using an ecoDriver system, the high accelerations will be reduced
- Using an ecoDriver system, the hard deceleration will be reduced
- Using an ecoDriver system, acceleration after being stationary will be less aggressive
- Using an ecoDriver system, the acceleration distribution will change before locations where a low speed is recommended by the system

Effect sizes in percentages (differences in % from relevant baseline)								
Hyp. Number & cat.	PI abbreviated	Road type	Controlled					Naturalistic
			Treatment (all systems) Type A	Embedded Type B	FeDS Type C	App Type D	Haptic Type E	App Type A
31 Accel Decel	95th percentile positive acceleration	Urban	13.12	8.54	5.17	2.11 (N.S.)	-4.38 (N.S.)	4.77
		Rural	4.43	13.21	8.42	1.61 (N.S.)	3.59 (N.S.)	3.06 (N.S.)
		Motorway	-1.2 (N.S.)	0 (N.S.)	5.8 (N.S.)	-	-	7.44 (N.S.)
		All road types	8.10	9.81	6.57	1.12 (N.S.)	-0.09 (N.S.)	4.57
32 Accel Decel	5th percentile negative acceleration	Urban	11.34	5.11	6.45	0.65 (N.S.)	0 (N.S.)	3.88
		Rural	3.64	14.65	7.14	-1.54 (N.S.)	4.65 (N.S.)	3.28 (N.S.)
		Motorway	0 (N.S.)	0 (N.S.)	3.7 (N.S.)	-	-	7.38
		All road types	7.46	9.02	5.80	-1.05 (N.S.)	1.92 (N.S.)	4.31
33 Accel Decel	maximum acceleration after stationnary	Urban	2.22	2.94	0.7 (N.S.)	1.77	-4.21 (N.S.)	-
		Rural	-	-	-	-	-	-
		Motorway	-	-	-	-	-	-
		All road types	-	-	-	-	-	-
34 Accel Decel Situation	95th percentile of the negative acceleration before intersections	Urban	4.95	4.74	3.94	-0.09 (N.S.)	3.50	-
		Rural	-0.94	4.38	3.64	-1.42 (N.S.)	1.01 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.12	4.59	3.84	-	-	-
35 Accel Decel Situation	95th percentile of the negative acceleration before zebra crossings	Urban	2.39	2.61 (N.S.)	4.19 (N.S.)	0.76 (N.S.)	5.25 (N.S.)	-
		Rural	-11.03	6.51 (N.S.)	15.75	-7.55 (N.S.)	-2.84 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	1.53	3.07	5.72	0.56 (N.S.)	4.30	-
36 Accel Decel Situation	95th percentile of the negative acceleration before speed bumps	Urban	6.43	10.95	16.96	4.49	2.06 (N.S.)	-
		Rural	12.37	12.82	12.89	11.98	-	-
		Motorway	-	-	-	-	-	-
		All road types	7.02	11.06	15.40	4.91	-	-

37 Accel Decel Situation	95th percentile of the negative acceleration before sharp curves	Urban	3.44	4.09	1.96 (N.S.)	-0.7 (N.S.)	8.24	-
		Rural	4.25	5.41	4.13	0.78 (N.S.)	1.27 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.88	4.80	3.28	0.18 (N.S.)	4.51	-
38 Accel Decel Situation	95th percentile of the negative acceleration at crests	Urban	0.65 (N.S.)	0.66 (N.S.)	0.59 (N.S.)	-	-	-
		Rural	4.18 (N.S.)	5.62	5.48 (N.S.)	-1.57 (N.S.)	-3.75 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	3.44	4.31	3.89	-	-	-
39 Accel Decel Situation	95th percentile of the negative acceleration before speed limit changes	Urban	1.42 (N.S.)	2.57 (N.S.)	2.87 (N.S.)	-2.01 (N.S.)	8.24	-
		Rural	4.11	4.94	1.69 (N.S.)	0.21 (N.S.)	1.27 (N.S.)	-
		Motorway	-	-	-	-	-	-
		All road types	2.96	3.83	2.09 (N.S.)	-0.4 (N.S.)	4.51	-

8.37.1 Results combining all systems

On average, all the tested systems showed improvements in acceleration: a change of about 10% was found in reducing 95th percentile of acceleration, 5th percentile of deceleration, and maximum acceleration. No impact is detected on motorways in the controlled trials. The naturalistic data deliver a different picture: high accelerations and decelerations are reduced on urban roads and motorways, but they are not significantly decreased on rural roads. Once again, the main benefits are observed for embedded systems, and for urban and rural roads. Neither the haptic systems nor the App softened deceleration before specific situations. The smallest impacts are observed at crests and before speed limit changes. Deceleration behaviour before specific situations have not been evaluated for motorways as such events did not exist.

8.37.2 Results across road types

Large benefits can be expected on urban and rural roads, but not on motorways. Results from the naturalistic studies may also provide evidence that eco-driving in the real world can also generate environmental friendly behaviour. In particular, based on previous results, it seems that on motorways, benefits on acceleration and deceleration behaviour can be greater. For deceleration at the specific situations, the impacts are similar for urban and rural roads. The observed changes are more linked to the situation type than to the road type itself.

8.37.3 Results across system categories

Both the App and the haptic variant did not generate any significant benefits. In controlled drives, only the embedded systems generated softer acceleration and deceleration. But even the nomadic eco-driving systems had a great impact when used in everyday driving in urban areas. For deceleration at the specific situations, the main benefits come from the embedded systems such as the FeDs. The ecoDriver App failed to achieve statistically significant results but the direction of the impact was the same as for the embedded systems.

9 Conclusions and discussion

Driving more efficiently is part of the solution to reduce greenhouse gas emissions from surface transport, but it is a highly complex task, comprising over hundreds of separate tasks (Walker et al., 2001). Drivers need to simultaneously control the vehicle, adjust their speed and trajectory according to the driving environment, deal with hazards, and make strategic decisions such as navigation to progress toward their goal (Young et al., 2010). Moreover, the green way to drive is often summarised into several pieces of simple advice easily understood by drivers (CIECA, 2007), but sometimes leading to a misunderstanding of the most fuel-efficient driving strategy.

Building a driving assistance system whose goal is to generate such a complex behaviour is of course a real challenge. In particular, real world usage of such systems can generate surprising behaviours, or just miss the target. It is important to understand that eco-driving not only relates to fuel savings, but also, and may be more, to a safer driving behaviour.

Within ecoDriver, several different systems were tested with different characteristics and features. Due to privacy issues from OEM partners, the only systems we can isolate are the one from the project: The FeDS and the App. These two systems are very different despite the apparent similar HMI. Other systems do not share the same HMI nor the same approach to generate eco-driving behaviour.

As a global picture of the ecoDriver results, it is confirmed that embedded systems (including FeDS), provide more benefits than nomadic systems such as the App. Embedded systems perform better because of their integration into the car and the ability to use car data information to display advice. On the other hand, non-embedded systems such as the App rely on internal computation mainly based on GPS information. It is therefore not surprising to observe this difference. Adding a haptic pedal can be useful, and produces small benefits, in the direction of smarter driving. Although usually non-significant, these results confirm that such a feature can be an important element of a larger system, and can increase acceptability. The poor performances of the App on controlled drives are counterbalanced by some positive results during the naturalistic experiment, especially in saving energy.

9.1 Energy and emissions

On average, the systems tested achieved a reduction of emissions and energy consumption ranging from 2.2% to 5.8%. It is encouraging to note that some of the non-significant results for the App during the controlled drives can turned into significant ones when used naturally. This could be considered as an evidence that such systems requires a long practice time before being really efficient.

9.2 Safety (speed, time headway, accelerations)

The effect of eco-driving on safety is not yet very well known, despite the usual idea that a smooth and smart driving style should increase safety. The ecoDriver experiments did not allow for observations of real crashes, and therefore rely on analysing speed, acceleration, and time headway, so called surrogate safety measures.

When the tested systems included a clear indication of the recommended green speed (embedded systems), the average speed when cruising was reduced by around 2% to 4%. A speed reduction of up to 10% was also observed for free driving in urban conditions. Similar effects are not observed for the ecoDriver App. This can be explained by the absence of a green speed indication. The ecoDriver App only displayed the current speed limit. Moreover, it is implemented in a different way than usual (for the App, the colour of the speedometer was green below the speed limit, and red above it). This information has apparently no impact on the way users of the App manage their speed.

Using ecoDriver systems, speed was also decreased in advance of specific situations that may induce safety problems. As recalled in Table 6, some systems had features to alert the driver when approaching a particular situation. All the systems alerted when approaching an intersection and all of them also provide information about the current speed limit to the driver. Before these last two situations, there is evidence of a decrease in speed for embedded systems, and also the FeDS. The ecoDriver App did not produce a significant reduction in speed except on the approach to rural intersections. For the haptic systems, a small additional speed reduction effect was seen on the approach to intersections. A significant reduction in speed is also observed before sharp curves on rural roads when using an embedded system, and also the FeDS. Almost no effect was found before speed bumps and at crests for all the systems together. These results allow us to derive the following two conclusions:

- When not announced, specific situations are not taken into account by the driver.
- When announced, specific situations generate a change in speed behaviour. This change is closely related to the quality of the system (integration, precision, reliability, HMI).

For example, a slight variation of time to display a needed alert due to different computational time, can impact the driver reaction time and so the acceptability of the HMI. Time headway (THW) is another safety measure to study. The impact of the systems on THW follows the same picture as for speed. THW was increased on average by between 6% and 10% for all road types, and for embedded systems only. Once again, the ecoDriver App, and the haptic variant, failed in reaching significance despite the positive direction of the results. Strong effects are also observed before intersections and speed limit changes for all the systems. Although the App and haptic systems did not reach significance, their results are in a positive direction. It is worth noting the strong impact of the embedded systems before speed limit changes on motorways. From these results, we can confirm that when the driver is not alerted about an upcoming situation, he or she will react in the usual way. In other words, there is no carry-over effect of using an ecoDriver system. When advised by the system, these situations are handled in a much safer way than without the system advice.

When considering accelerations and decelerations, they are decreased when using an embedded system on urban and rural roads. Other conditions failed to reach significance. Intersections proved to be well anticipated by drivers, with smooth decelerations. Despite the absence of an alert from the systems, zebra crossings and speed bumps were also very well anticipated. Globally, the significance is

better than for the speed results. The variability of the acceleration signal is much greater than the variability of speed. It is therefore more difficult to detect a change in average speed than on 95th percentile of acceleration. The exception is when an effect on speed is expected, such as being alerted to a speed change: here we observe less impact on accelerations than on speed.
Results for the naturalistic part of the data are once again contradictory. Accelerations and decelerations are smoother on urban roads than for the controlled studies, while they are harsher on motorways. The reason for this observation is not clear.

9.3 Golden rules

All the systems tested, except the haptic version, induced positive effects on the four indicators characterising eco-driving. The embedded systems induced larger benefits than the App. The results prove that the ecoDriver systems generally induce the following driving behaviour: shifting gear up more quickly, driving with a lower engine rpm, smoother speed profiles, and increased usage of engine brake. Among these indicators, the smoothness of the speed profiles (PKE) is more correlated with fuel consumption. All these different aspects of the change in driving should translate into energy reduction and safer behaviour. But when eco-driving is only partially applied, most of the benefits can be lost. The application of the eco-driving golden rules is significant for all four rules on rural roads only; therefore it is not surprising that significant fuel savings are obtained for this road type.

Applying the golden rules on urban roads is difficult because there are many constraints related to safety that are a priority for the driver. Eco-driving in urban areas can become closer to safe driving than green driving. On the other hand, there are very few constraints on motorways, and driving there is usually smooth. On motorways, it is not always easy to apply some of the rules for eco-driving that can help to save fuel (use engine brake for example). This explains the non-significant results obtained for energy savings on motorways.

Results obtained for naturalistic data are in line with the findings from the controlled tests. Drivers were less compliant with the engine rpm related rules, but the changes were still in the correct direction. However, they did not comply in terms of the smoothness of the speed profiles and engine brake usage. On average, speed profiles were flattened, mainly on urban roads. The engine brake driving technique is less used on motorways. Perhaps drivers preferred using another technique consisting of maintaining momentum in neutral instead of in gear.

The golden rules have a number of issues: they are expressed differently from country to country, and they are not directly linked to energy savings. For example, when trying to anticipate surrounding traffic in urban environment and so decelerate smoothly, one could be overtaken by other vehicles and therefore lose position in traffic time and as a result also lose some of the energy saving benefits. It is therefore the case that one might not obtain large fuel savings even when following the golden rules.

9.4 Main findings

The main findings of this study can be summarised as follows:

- Using ecoDriver systems in real conditions, and applying a conservative statistical approach, energy savings range from 2% to 6%. This is less than was aimed for, but perhaps closer to plausible long-term benefits. For some drivers, the benefits were considerably larger.
- The ecoDriver systems proved to have strong positive impacts on speed, time headway, and accelerations and decelerations. This could translate into less severe crashes.
- The ecoDriver systems proved to generate a driving style compliant with the golden rules of eco-driving.
- Advice on eco-driving in specific situations generates a change in driving behaviour. This change is closely related to the quality of the system (integration, precision, reliability, HMI).
- Nomadic systems change the driving behaviour in a good direction, but benefits are smaller than when using an embedded system.
- The naturalistic experiments gave similar results to the controlled studies, although with lower effect sizes. Contrary to the first three rules, applying rule 4 (engine brake) seems difficult for naturalistic drivers, or perhaps another technique is preferred.
- Naturalistic experiments are recommended for studying the overall long-term and realistic impact of eco-driving. Significant benefits can be expected even when using a nomadic system.

10 Implications and lessons learned

10.1 Implications

The collection of the data in WP43 was a vital input to the WP53 microsimulation work which in turn informed the scaling up in WP54.

Like many ambitious projects, ecoDriver experienced some delays which turned into a request for a nine month extension. Only 6 months were granted, so the whole statistical analysis process and the scaling-up had to be shortened. In order to address this situation and maintain high scientific standards, the analyst team adopted several approaches:

- Use of a common methodology and a common analysis software (e.g. R Software).
- Organisation of workshops a long time in advance to share deep statistical knowledge and practical experience with the software.
- Sharing of a fine-tuned and flexible analysis code.
- Organisation of workshop to write the shared analysis code.
- Automating of the data analysis chain, from code to formatted tables, to allow for a quick update of the results.

The outcome of this organisation is a common knowledge across partners of both a suitable methodology for FOT (Using mixed models to take correlation into account), and the corresponding free R code to perform this analysis in another contexts. Of course, the project also experienced some difficulties. The time needed for the data treatment (quality check, data enrichment, data reduction, and computations) has been underestimated. This was especially true for the naturalistic part of the ecoDriver experiment which leads to a large amount of data to be processed. This process is still ongoing so the project could certainly have done better. Nevertheless, processing such an amount of data requires to be well prepared, probably beyond the project itself. As a consequence, only a small part of the collected naturalistic data was analysed within this deliverable.

Several issues were encountered during the four years of the ecoDriver project, but the project team efficiently worked hard to find solutions. These solutions are shared publically and described in this section. We believe ecoDriver reached the promised goals by adopting a common analysis methodology and tools, but most of all, by relying on an efficient and very reactive team. Involvement and motivation of the partners are always a key to the success of such large scale projects.

10.2 Lessons learned

The ecoDriver project is a collaborative project, in the sense that all partners have engaged together to share their collected data into a common database. The research questions list have been divided across partners, so that each partner is in charge of analysing one aspect, using data from all partners. It has been decided to use open source software (R software) for statistical computations. This improves the reliability of the approach by guaranteeing the consistent use of the same methods and algorithms. The adopted approach was different from that of previous FOTs for which each partner was in charge of analysing its own data collected during their trials. Although successful, this approach revealed other drawbacks that may require further attention for the upcoming projects. These are detailed below.

i. Adopt a single experimental design for all experiments, with sufficient sample sizes

Several partners are usually involved in the experiment part of any large scale project. Within ecoDriver, eight different partners took care of a specific experiment, whose design was linked to the scientific question studied by the team. Despite there being recommendations for a harmonised experimental design, this was not always possible due to technical or partner-specific constraints. This led to experiments with different car types, different logging equipment, different design, and therefore a different structure of the final data set. This situation proved to be very difficult to deal with when trying to reach the statistical analysis step. When a common statistical analysis approach is adopted within the different site, it is recommended to harmonise as much as possible the different study designs. Embedded into the experimental design issue, the sample size is also a critical point that can decrease statistical power of the analysis. Limited data was available within the ecoDriver project to assess long term effects of the systems. It is very important to ensure that sample sizes allow for all the scheduled impact studies.

ii. Ensure project partners to share the data required for the analysis

When beginning a project that includes a large data collection part, it is very difficult to figure out the final data needs for analyses. Each partner has to collect data in its own way, according to internal technical expertise, which may involve proprietary competencies. When several partners are collecting data differently, using their own test vehicles and protected knowledge, it is probable that some of them will need to protect part of the data collected. Within ecoDriver, despite a general data sharing policy, some partners (OEM or academic) did not share their fuel consumption raw measures for economic reasons. For the needs of energy related analysis, an emission model from TNO was required to obtain instant fuel consumption data. Delays and additional efforts have been the price to pay for this late issue. It is therefore recommended to write down as early as possible a partner agreement for data sharing issues. Any data analyses requirements should be reflected in this agreement to avoid weak statistical conclusions at the end of the project.

iii. Work in close collaboration between database managers and data scientists

The management of the database was done by a single partner (CTAG) which received data from all experimental sites. This partner was responsible for the reduction of the data, into tractable performance indicators, suitable for statistical analyses. Partners transmitting data to CTAG had to comply with decisions taken very early in the project and not fully in line with the final constraints. Also, detailed algorithms had to be transmitted to CTAG for local implementation. The whole process of implementing the database locally, transferring data in a good format, quality checking that data, transmitting PI codes, and also validation and quality checking of the local implementation, proved to take longer than expected. For further studies, it is recommended to clarify this process as much as possible during the proposal phase, designating responsibilities, beginning and ending date of sub projects and tasks, description of the code to be transmitted, etc.

iv. Agree on a Gantt chart for the whole data management chain and schedule a time margin for unpredictable delays

The time required for data management (importation, quality check, enrichment, PI computation and data reduction, validation and quality checking of the results) proved to be often underestimated. Indeed, this step has to deal with all other previous delays. For example, this could be delays in the experiment due to technical difficulties or legal issues. Among several partners, just one being delayed induces delays for the whole data management process. So, increasing partner numbers increases the odds of becoming delayed in data management. As this is very probable, it is recommended to take this delay into account when planning the project instead of planning something more ambitious but very risky. A three month additional time slot should be enough to absorb any reasonable deviation from the plan. The data management and treatment task should always start as soon as the first data are collected within the project.

v. Take account of the confidentiality of collected data into the data management process

Dealing with a unique and centralised database during the project implies that all partners are transmitting data to that local repository. For confidentiality issues, private partners may require a different process. Instead of transferring data to another place, the ecoDriver common database scheme and data treatment code has been exported as a local copy of the centralised database. This way allowed for relevant partners to apply locally the exact same computations as the ones applied in the centralised database. Aggregated values (PIs) can then be shared at the project scale, while preserving confidentiality of the raw data. It is recommended to schedule enough time to build a common database structure that can be imported locally for individual partner computations.

vi. Use common open source tools and methodology, and share the code

A free and open source statistical software (the R software) was used as a common tool for statistical results. Experts involved in the project took care of developing and sharing suitable codes for the scheduled analysis (taking into account data correlation). Although based on complex methods, the statistical analysis proved to be easily done by partners even those without any deep statistical knowledge. Harmonised and robust results have been obtained. It is recommended to use open source statistical software, involve people experienced with it, and develop a common code suitable for performance indicator comparisons based on FESTA methodology.

vii. Automate the statistical analysis process, from code to formatted tables

While trying to follow the very ambitious time plan, the ecoDriver team took the time to develop an automated data analysis chain. A simple process has been designed to allow for simplicity and quick reproduction of updated results. The final user only had to copy the good files and change some paths in the code to get several excel tables filled with formatted tables according to the deliverable template. This proved to be very efficient and very practical for the final user. The ecoDriver team believe it is a good practice, especially when combined with a shared code using open source software.

viii. Do not underestimate the time needed for database computations

Within a large-scale field operational test (FOT), thousands of probe vehicle traces are collected, sometimes using a naturalistic driving approach. The data reduction process, which consists of dividing the trips into comparable situations, and computing related PIs, can induce very long computation times. If this process is not parallelised, several months (between 3 and 6) are needed to get reduced data suitable for analysis. It is strongly recommended not to underestimate the time needed for computation on large databases.

ix. Adopt a statistical methodology in line with the actual standards

A well-known fact is the presence of correlation in data collected during FOTs. Among different trips with the same driver, some driver characteristics may not change (sensation seeking for example). Such constant differences may impact the way drivers use the tested systems. It is therefore recommended not to use the classical analysis of variance technique, but use suitable methods developed for such cases: The generalised linear mixed models (GLMM), or the generalised estimated equations (GEE). Such analysis methods are available within the free and open source R software. In order to protect against false conclusions and obtain reliable results, ecoDriver followed the GLMM approach together with a 5% level of significance.

x. Plan theoretical and practical workshops about statistical methodology before starting to analyse data

Analysing data is the very last step of such a project, just before the scaling-up step. When started, the time available is usually short, and there is no time for theoretical questions. One year before the statistical analysis, ecoDriver decided to adopt a common open source tool for which few partners was familiarised. Practical workshops, together with theoretical courses, were set up in order to share a common knowledge among partners. This way to work allowed for working meetings devoted to developing common codes, which proved to be very efficient. It is recommended to share a common theoretical and practical knowledge of the statistical methods and tools used, a long time before the analysis has to start.

xi. Scaling-up the results should be scheduled sequentially after the statistical analysis is done

When delays accumulate, the time for analysis and scaling-up is strongly constrained. If these activities are scheduled in parallel, there is a risk not to be able to use the statistical results for the scaling-up. It is advised to schedule enough time to perform the statistical analysis and the scaling-up sequentially.

References

Andrieu C, Saint Pierre G, 2012. Using statistical models to characterize eco-driving style with an aggregated indicator. Intelligent Vehicles Symposium
2012, June 3–7, 2012, Alcalá de Henares, Spain.

Beusen, B., Broekx, S., Denys, T., Beckx, C., Degraeuwe, B., Gijsbers, M., Scheepers, K., Govaerts, L., Torfs, R., Panis, L.I., (2009). Using on-board logging devices to study the longer-term impact of an eco-driving course. Transp. Res. Part D 14, 514–520.

CIECA (2007). CIECA internal project on 'Eco-driving' in category B driver training & the driving test. CIECA: International commission for driver testing. Available at http://www.transport-research.info/sites/default/files/project/documents/20091210_155535_71033_ECODRIVEN%20Final%20Report.pdf.

Dingus, T.A. et al. (2006). The 100-Car Naturalistic Driving Study: Phase II – Results of the 100-Car Field Experiment. Report No. DOT HS 810 593, National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington, D.C.

Dozza, M., Bärgman, J. and Lee, J. D. (2012). Chunking: a procedure to improve naturalistic data analysis Accident Analysis & Prevention. Vol. 58, pp. 309–317.

Ericsson, E., 2001. Independent driving pattern factors and their influence on fuel-use and exhaust emission factors. Transport. Res. Part D: Transp. Environ.
6, 325–345.

FESTA Handbook, Version 2, FESTA consortium, 19 August 2008, http://www.its.leeds.ac.uk/festa/, http://www.its.leeds.ac.uk/festa/downloads/FESTA%20Handbook%20v2.pdf

Guo, F. and Hankey, J. (2009). Modeling 100-Car Safety Events: A Case-Based Approach for Analyzing Naturalistic Driving Data. Report 09-UT-006. The National Surface Transportation Safety Center for Excellence, Virginia Tech Transportation Institute (VTTI), Blacksburg, Virginia.

Hornik, K. (2015). R FAQ. https://CRAN.R-project.org/doc/FAQ/R-FAQ.html
Retrieved 22 January 2016.

Kircher, K. and Ahlstrom, C. (2010). Predicting visual distraction using driving performance data. Annals of Advances in Automotive Medicine, Vol. 54: pp.333-342.

Kircher, K., and Ahlstrom, C. (2013). The driver distraction detection algorithm AttenD. In M. A. Regan, J. D. Lee & T. W. Victor (Eds.), *Driver distraction and inattention: Advances in research and countermeasures* (pp. Chapter 2). Surrey, UK: Ashgate.

Kircher, K. Ahlström, C., Blanco, R. et al. (2012). D41.1: Performance indicators and ecoDriver test design. ecoDriver project. Retrieved from www.ecodriver-project.eu

Kircher, K. and Ahlstrom, C. (2015). Evaluation of methods for the assessment of minimum required attention, VTI report number R872A.

Liang, K.-Y. and Zeger, S. L. (1986). Longitudinal data analysis using generalized linear models. Biometrika, Vol.73(1), pp. 13-22.

R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Walker, G.H., Stanton, N.A. and Young, M.S. (2001). Hierarchical Task Analysis of Driving: A New Research Tool. In M.A. Hanson (Ed), Contemporary Ergonomics, Taylor & Francis Ltd., London, 435-440.

Young, M. S., Birrell, S. A. and Stanton, N. A. (2010). Safe driving in a green world: A review of driver performance benchmarks and technologies to support “smart” driving, Applied Ergonomics, Vol 42., pp533-539.

For more information about ecoDriver

ecoDriver project
Prof. Oliver Carsten
University of Leeds (coordinator)
Woodhouse Lane
Leeds LS2 9JT
United Kingdom

O.M.J.Carsten@its.leeds.ac.uk
www.ecodriver-project.eu

How to cite this document

Saint Pierre, G., Brouwer, R, Hogema, J. et al. (2016). D43.1: Eco-driving in the real-world: behavioural, environmental and safety impacts. ecoDriver project. Retrieved from www.ecodriver-project.eu