ecoDriver

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

Executive Summary

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.

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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

Partner 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

Executive summary

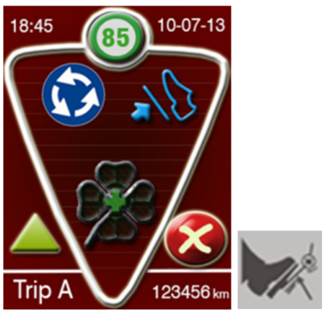
Under real world driving conditions, the ecoDriver project tested nine different eco-driving support systems developed within the project. The ecoDriver systems differed from each other, but so also did the vehicles used, the data collection system, and the experimental plan. These differences made the 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.

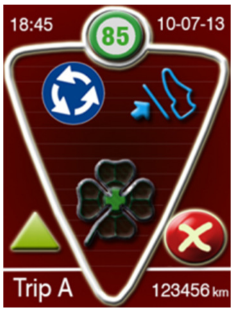
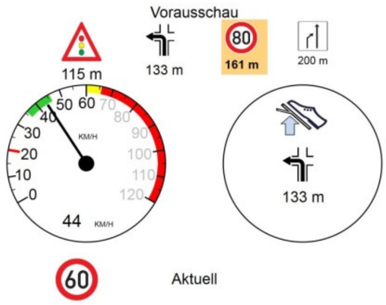
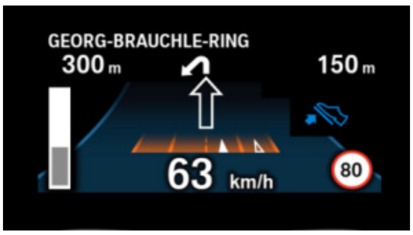
This deliverable reports the different experiments together with the system tested. We describe the common methodology that has been set up for the project, which is based on open source software (R software). Results are provided in a summarised form (Table 4) followed by detailed comments and discussions of the implications.

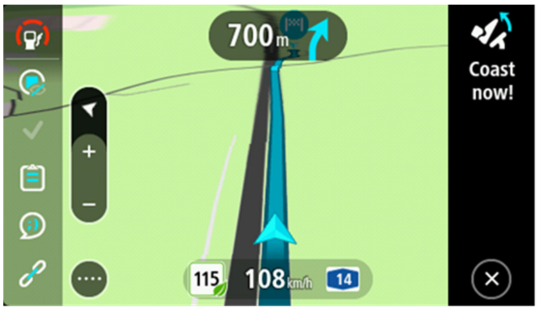
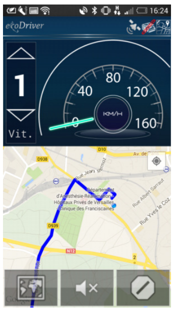
1. Overview of the systems and experimental designs

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.

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

System	Screen shot	HMI / Information	Vehicle
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
BMW	 	Visual (dashboard and HuD) / CAN information / map information	Passenger car

System	Screen shot	HMI / Information	Vehicle
TomTom		Visual / OBD2 connection / map information	Trucks and vans
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.

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

Test site	Design	Number participants	Controlled / ND
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[1]	10	ND
TomTom (LCVs)	Baseline, previous TomTom eco-driving solution, system1, system2, system31	10	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)**[2]	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. Hypotheses and analysis methods

An initial list of hypotheses was developed in an earlier stage of the project. 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 3.

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

[2] 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: 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
		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:

Main section in deliverable	Research Question category	Hypothesis number	Hypothesis
		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
		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 1. The chosen aggregation method follows the recommendations of Dozza and Bärgman (2013).

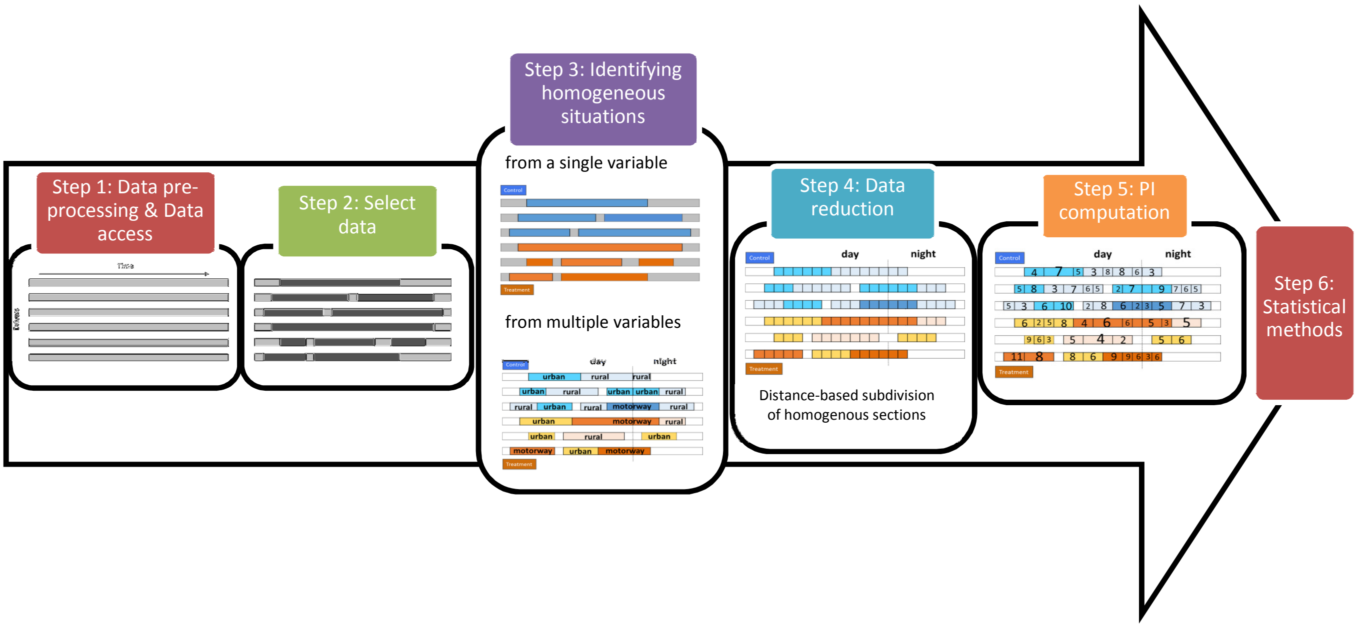


Figure 1: Overview of the data treatment and analysis process for a classical research hypothesis.

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 an 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 2.

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 2 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.

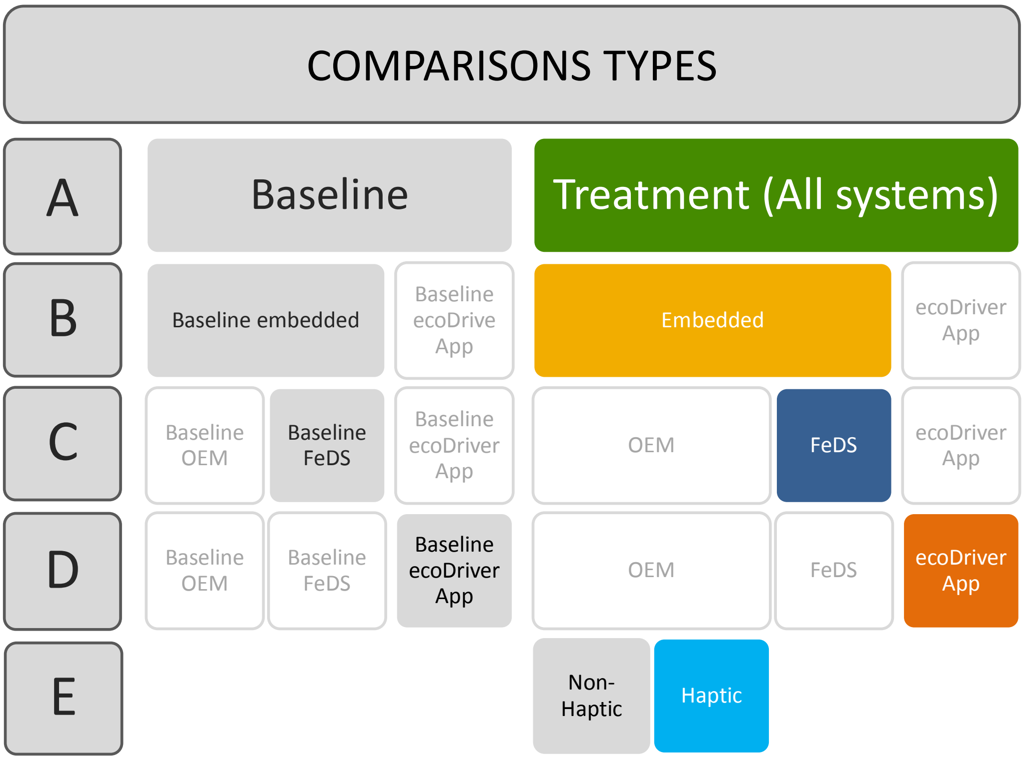


Figure 2: Overview of comparison types A through E

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). The different research questions were 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.

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 in Table 4. 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.

The results will be provided throughout the document in the form of summary tables such as Table 4 which summarises all ecoDriver results together. The 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. 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, no there was no radar on the vehicles in the naturalistic trials, so that no measure of time headway was possible.

Table 4: 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)								
			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
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[3]	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.)
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	-

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

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.)	-
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.)	-	-
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.)	-	-
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
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	-	-
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.

3.1 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.

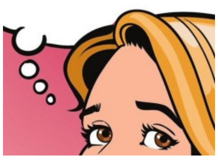
iii. **When grouping the systems by categories** the ecoDriver embedded systems (which use detailed vehicle data from the CAN bus or OBD2) perform better than the App, with fuel savings of up to 6% and NOx up to 5.7% on rural roads. Individually, the FeDS has a significant impact on both fuel/CO_2 and 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%.

3.2 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 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.

3.3 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 on the approach to intersections.

3.4 Main findings — time headway

THW DISTANCE / SITUATIONS

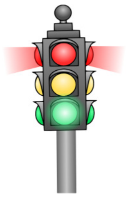
- Using an ecoDriver system, the time headway distribution to leading vehicle will change
- Using an ecoDriver system, there will be shorter distances to vehicles before safety critical locations

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 %).

3.5 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.

3.6 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 ecodriving 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.

3.7 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.

3.8 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.

3.8.1 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.

3.8.2 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.

3.8.3 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. Large benefits can be expected even when using a nomadic system.

3.9 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 can briefly be described as:

- Adopt a single experimental design for all experiments,

- 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.

For more information about ecoDriver

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