Safety impacts of cooperative systems

Risto Kulmala, Pirkko Rämä and Niina Sihvola

VTT Technical Research Centre of Finland
P.O. Box 1800, FI-02044 VTT, Finland

1. Introduction

The development of intelligent vehicle safety systems is rapidly moving from autonomous systems relying on vehicle's own sensors towards cooperative systems utilising communications between vehicles or between infrastructure and vehicles. The paper discusses the results of two recent European studies assessing the socio economic impacts of intelligent vehicle systems, including a number of cooperative systems.

The first study, eIMPACT, studied 12 different systems and their impacts in 2010, 2020 and with 100% market penetration. The systems were:

- Electronic Stability Control
- Full Speed Range ACC
- Emergency Braking
- Pre-Crash Protection of Vulnerable Road Users
- Lane Change Assistant (Warning)
- Lane Keeping Support
- NightVisionWarn
- Driver Drowsiness Monitoring and Warning
- eCall (one-way communication)
- Intersection Safety
- Wireless Local Danger Warning
- SpeedAlert

Of these 12 systems, the last four are representing cooperative systems, whereas the first eight are autonomous ones.

The second study, CODIA, studied five cooperative systems and their impacts in 2020, 2030 and with 100% market penetration. The systems were:

- V2I Intelligent speed adaptation
- V2I Reversible lane control
- V2V Local danger warning
- V2V Post crash warning
- V2X Intersection collision warning

As the cooperative systems are new and their specifications have not been determined to any level of detail, the work was carried out on the basis of a number of assumptions based on system functionalities, technologies, HMI, costs, vehicle market penetration, infrastructure coverage, and effects on driver and travel behaviour. The assumptions and findings in different phases were validated with consultations with experts from the European Commission, related European research projects, industry and the academia as well as in a final workshop.

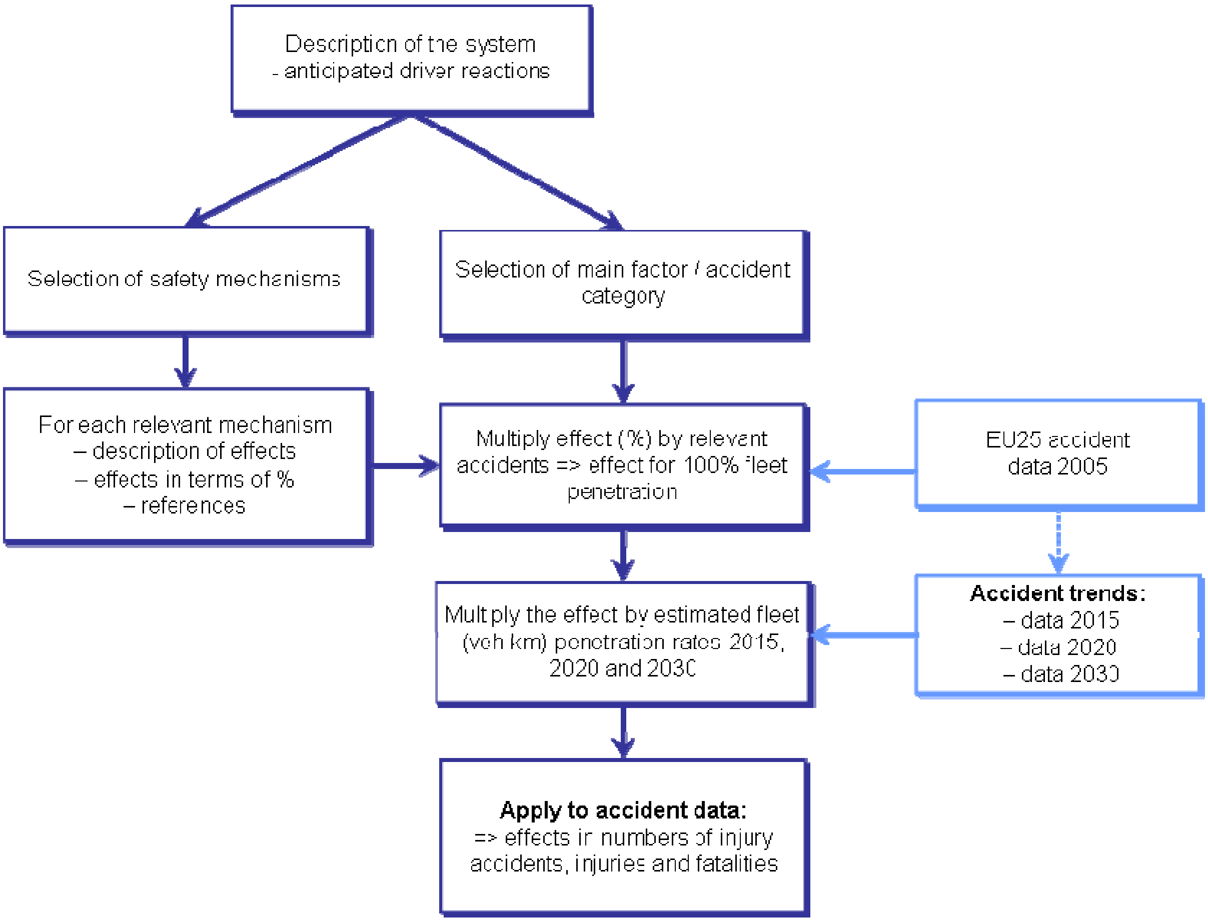
2. Safety assessment methodology

Draskóczy, Carsten and Kulmala (1998) compiled a list of mechanisms, via which ITS affects safety. The list is the following:

1. Direct in-car modification of the driving task by giving information, advice, and assistance or taking over part of the task. This may influence driver attention, mental load, and decision about action (for example, driver choice of speed)
2. Direct influence by roadside systems mainly by giving information and advice. Consequently the impact of this influence is more limited than of the in-vehicle systems.
3. Indirect modification of user behaviour in many, largely unknown ways. The driver will always adapt to the changing situation. This is often called behavioural adaptation and will often not appear immediately after a change but may show up later and it is very hard to predict. Behavioural adaptation may appear in many different ways (for example, by change of usage of the car, by change of headway in a car following situation, by change of expectation of the behaviour of other road users)
4. Indirect modification of non-user behaviour. This type of behavioural adaptation is even harder to study because it is often secondary. Non-equipped drivers may for example change their behaviour by imitating the behaviour of equipped drivers (for example, driving closer or faster than they should, not having the equipment).
5. Modification of interaction between users and non-users. ITS will change the communication between equipped road users. This change of communication may influence the traditional communication with non-equipped road users. To a large extent this problem may appear in the interaction between drivers and unprotected road users.
6. Modification of road user exposure by for example information, recommendation, restrictions, debiting. This is certainly an area where introduction of ITS will have a large impact for example by changing travel pattern, modal choice, route choice etc.
7. Modification of modal choice by, for example, demand restraints (area access restriction, road pricing, area parking strategies), supply control by modal interchange and other public transport management measures, travel information systems. Different travel modes have different accident risks, therefore any measure which influences modal choice, has also impact on traffic safety.
8. Modification of route choice by route diversions, route guidance systems, dynamic route information systems, hazard warning systems monitoring incidents. Different parts of the road network, i.e. different categories of roads, have different accident risks, therefore, any measure which influences route choice by diverting traffic to roads of different category, has also impact on traffic safety.
9. Modification of accident consequences by intelligent injury reducing systems in the vehicle, by quick and accurate crash reporting and call for rescue, by reduced rescue time.

The safety mechanisms listed above formed the backbone of the safety assessment methodology as indicated in Figure 1.

Figure 1: Safety assessment methodology applied.



The safety effects were assessed with a method developed in the eIMPACT project (Kulmala, Rämä, Sihvola & Schirokoff, 2008). The method addresses all three dimensions of road safety: (1) exposure, (2) risk of a collision to take place during a trip and (3) risk of a collision to result in injuries or death. These dimensions are covered by the nine behavioural mechanisms. With these mechanisms, the analyses covered not only the direct intended effects of systems but also the indirect and unintended effects, including behavioural adaptation in long term use. In addition, the method takes into consideration that the effects will vary according to road conditions and circumstances. Hence, all effects on safety should be covered by the analyses.

First, safety impact assessment started with the system specifications, including anticipated driver reactions. Secondly, the relevant safety mechanisms were selected for each system studied, and the expected changes in driver behaviour were described. Each system was compared to the base or reference case with no system. Thirdly, based on existing knowledge, a numerical percentage value for the change in fatalities and injuries was estimated for each safety mechanism. The estimates were motivated with references found in literature and other evidence available. Finally, the effect estimates were applied to the EU25 road accident data utilising the forecasted safety trends up to 2030 to provide estimates about the effects of the systems in terms of fatalities, injuries and accidents saved by the system in 2020 and 2030 as well as in the case of 100% system penetrations in the vehicle fleet.

The benefit and cost assessment methodology relied on standard discounted flow and cost benefit analysis techniques. Both Net Present Value (NPV) and Benefit to Cost ratio were used as indicators in the socio economic assessment. The assessment covered the in-vehicle system costs, investment and maintenance/operation costs of the required infrastructure as well as changes in accident costs, time costs, emission costs and fuel costs due to the systems. A multi-criteria table was compiled for assessing qualitatively the major benefits or costs associated with the use and utilisation of the systems, which cannot be monetised. This table also included the relevant risks, uncertainties or opportunities. The methodologies developed in the SEiSS (Abele et al., 2005) and eIMPACT (Baum et al., 2008) were applied in the socio-economic assessment.

3. Data

The work started with a literature survey for obtaining information on the system characteristics, costs, and impacts of the cooperative systems and systems with partly similar functionalities. Contacts were established with the cooperative system R&D projects of COOPERS, CVIS and SAFESPOT in order to obtain more detailed data on system specifications.

At the same time basic data for the impact assessments were compiled. The accident data for EU25 was the data base collected for the eIMPACT project by the parallel TRACE project. As it is obvious that road safety would improve considerably also without the deployment of the cooperative systems, predictions were made of the accident, injury and fatality trends up to 2030. (Wilmink et al., 2008; Kulmala et al., 2008)

The vehicle fleet and mileage data and predictions was compiled from public European statistics, in addition to which also predictions from eIMPACT were utilised. The eIMPACT methods (Wilmink et al., 2008) were used to estimate the vehicle fleet and vehicle mileage penetrations of the studied systems up to 2030. As the uncertainties of vehicle penetrations were large, both a low (business as usual) and a high (accelerating deployment with various means) penetration scenario was estimated for each system.

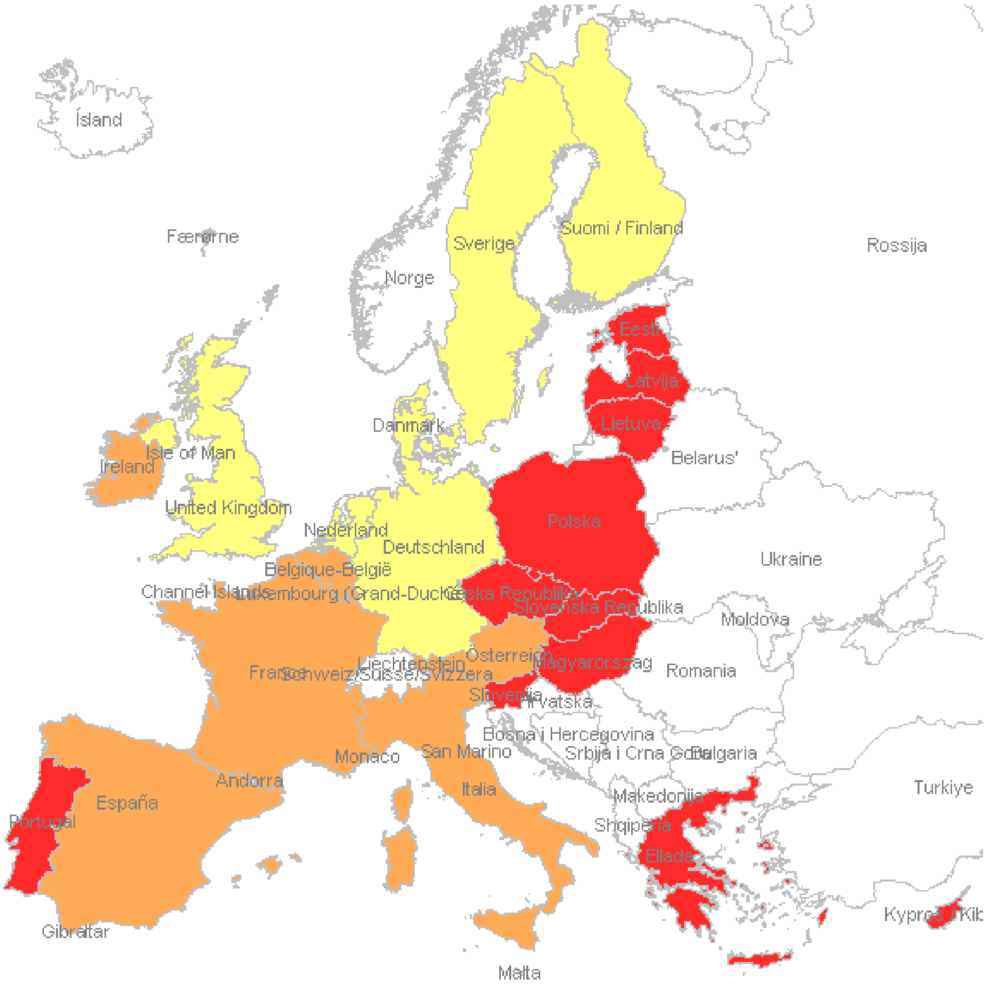
With respect to the derivation of exhaust emission, a combination of the TRENDS database and the current DG Environment FLEETS project was utilised.

Traffic data was also based on the data compiled for the eIMPACT study up to 2020, and projected forwards to 2030. Cost estimates were based in the costs available from eIMPACT as well as the cooperative R&D projects. (Wilmink et al., 2008; Kulmala et al., 2008)

4. Forecasts utilised

The eIMPACT project (Wilmink et al. 2008) produced the forecasts for road safety developments until 2020 with the help of a predictive model for fatality rates (against vehicle kilometres and vehicle stock) for each of the three country clusters within EU25. The country clusters are shown in Figure 2.

Figure 2: The three clusters in EU25 accident data (cluster 1 = yellow, cluster 2 = orange, cluster 3 = red). (Wilmink et al. 2008)



The actual predictions for fatalities, injuries and accidents up to 2030 were then calculated as the products of the fatality rate and vehicle kilometre predictions for each cluster. This project utilised the forecasts provided by eIMPACT but extrapolated the estimates to 2030. With regard to injuries (and injury accidents), specific models were calculated in this study as the development of injuries has not been as positive as for fatalities during the period 1991-2006.

The injury accident numbers 1990-2006 were obtained from European statistics (European Commission 2007).

Exponential models of the form Injury rate = $A\ e^{Year\ +\ B}$ fitted using the SPSS statistical software for each cluster. For injury rate models, the coefficients for determination (R2) varied between 0.78 and 0.93.

As the forecasts are used in transforming the accident data from 2005 to the future years, the results are shown in Table 1 as ratios to be used in changing the numbers of 2005.

Table 1: Based on accident prediction models, ratios to be used in changing the accident data from 2005 to make accident data forecasts up to 2030. (Kulmala et al., 2008)

Year	Cluster 1	Cluster 2	Cluster 3
Ratio to injury rate of 2005			
2010	0.844	0.831	0.730
2015	0.712	0.691	0.533
2020	0.600	0.574	0.389
2025	0.507	0.477	0.284
2030	0.427	0.397	0.207
Ratio to vehile kilometres in 2005			
2010	1.045	1.041	1.154
2015	1.077	1.074	1.268
2020	1.111	1.107	1.395
2025	1.139	1.135	1.506
2030	1.162	1.158	1.597
Ratio to number of fatalities in 2005 (eIMPACT until 2020)			
2010	0.819	0.850	0.783
2015	0.000	0.000	0.000
2020	0.512	0.530	0.460
2025	0.000	0.000	0.000
2030	0.000	0.000	0.000
Ratio to number of injuries in 2005			
2010	0.881	0.865	0.842
2015	0.767	0.742	0.676
2020	0.667	0.636	0.542
2025	0.577	0.541	0.427
2030	0.496	0.459	0.331

The market penetrations of new vehicles with OEM systems and penetrations of nomadic/retrofit systems were estimated as expert judgement. With the help of methods developed in eIMPACT (Wilmink et al., 2008), these were then transformed into fleet and fleet vehicle km penetration rates. An example of the forecasts is shown in Table 2.

Table 2: Low and high penetration values (%) of V2V local danger warning in new vehicles as OEM system, all vehicles as retrofit system, whole vehicle fleet and all driven vehicle km in EU25 in 2020 and 2030 for cars, goods vehicles and buses.

V2V Local Danger Warning

Vehicle type / year	New vehicles OEM equipped LOW	New vehicles OEM equipped HIGH	All vehicles retro-fitted LOW	All vehicles retro-fitted HIGH	Vehicles equipped of fleet LOW	Vehicles equipped of fleet HIGH	Fleet vehicle km equipped LOW	Fleet vehicle km equipped HIGH
Cars / 2020	2 %	7 %	1 %	10 %	2 %	12 %	2 %	12 %
Goods Vehicles / 2020	5 %	20 %	1 %	5 %	2 %	11 %	3 %	13 %
Buses / 2020	5 %	20 %	1 %	5 %	2 %	9 %	3 %	11 %
Cars / 2030	20 %	60 %	20 %	30 %	26 %	49 %	27 %	53 %
Goods Vehicles / 2030	20 %	80 %	5 %	20 %	13 %	53 %	16 %	63 %
Buses / 2030	20 %	80 %	5 %	20 %	12 %	47 %	14 %	56 %

5. Results

The safety impacts of the cooperative systems studied in CODIA are presented in Table 3. Concerning the safety impacts of the five cooperative systems, Dynamic speed adaptation system shows most substantial impacts to decrease fatalities and injuries in traffic. The impacts increase substantially from the low 0.5% of 2020 to about 4% in 2030. Most of the effects are derived from the speed limit related speed adaptation as the coverage of the I2V infrastructure is expected to be quite low even in 2030.

Table 3: The effects of five cooperative systems on fatalities and injuries in EU25 in five scenarios: 100% vehicle fleet penetration, 2020 low penetration, 2020 high penetration, 2030 low penetration and 2030 high penetration. (Kulmala et al., 2008)

	Fatalities				
System	100 %	2020 low	2020 high	2030 low	2030 high
Dynamic speed adaptation	-7.2 %	-0.3 %	-1.0 %	-3.2 %	-4.2 %
Reversible lanes	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
Local danger warning	-4.2 %	-0.2 %	-1.0 %	-2.1 %	-3.9 %
Post crash warning	-1.4 %	-0.2 %	-0.8 %	-0.7 %	-1.1 %
Cooperative intersection collision warning	-3.7 %	0.0 %	0.0 %	0.0 %	-0.2 %
	Injuries				
System	100 %	2020 low	2020 high	2030 low	2030 high
Dynamic speed adaptation	-4.8 %	-0.2 %	-0.7 %	-2.1 %	-2.5 %
Reversible lanes	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
Local danger warning	-3.1 %	-0.1 %	-0.8 %	-1.6 %	-2.9 %
Post crash warning	-0.7 %	-0.1 %	-0.5 %	-0.3 %	-0.6 %
Cooperative intersection collision warning	-6.9 %	0.0 %	0.0 %	-0.1 %	-0.4 %

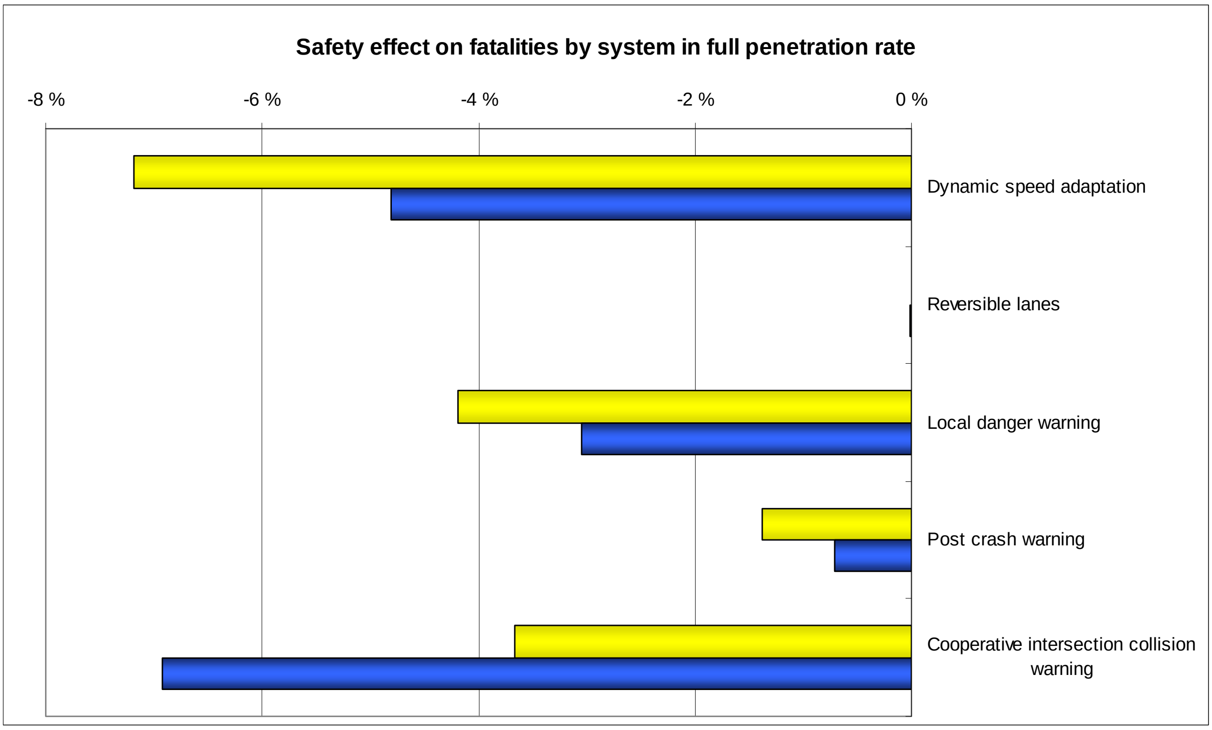
The Reversible lane system decreases the fatalities and injuries on the sections equipped. However, a very small part of the motorway and urban network are suitable for the system with regard to their traffic flows. The system is planned to improve fluency of the traffic flow, and previous research has shown considerable negative impacts on traffic safety. The results indicated that these negative impacts can probably be avoided with a cooperative variant of the system.

The reductions of accidents have also large indirect benefits in terms of decreases in congestion costs, which are considered in the socio-economic assessment.

Even if the predicted safety impacts for the target years are in general quite small, the cooperative systems showed considerable potential to contribute to improved traffic safety (Figure 3).

Dynamic speed adaptation showed most potential (-7%) to decrease fatalities. The cooperative intersection collision warning and local danger warning comes next (-4%). The potential to prevent injuries is most substantial for cooperative intersection collision warning (7%) followed by dynamic speed adaptation (5%).

Figure 3: The effect of the five CODIA systems on fatalities (light yellow) and injuries (dark blue) in full penetration. (Kulmala et al., 2008)



The results concerning the systems studied in eIMPACT are shown in Figure 4.

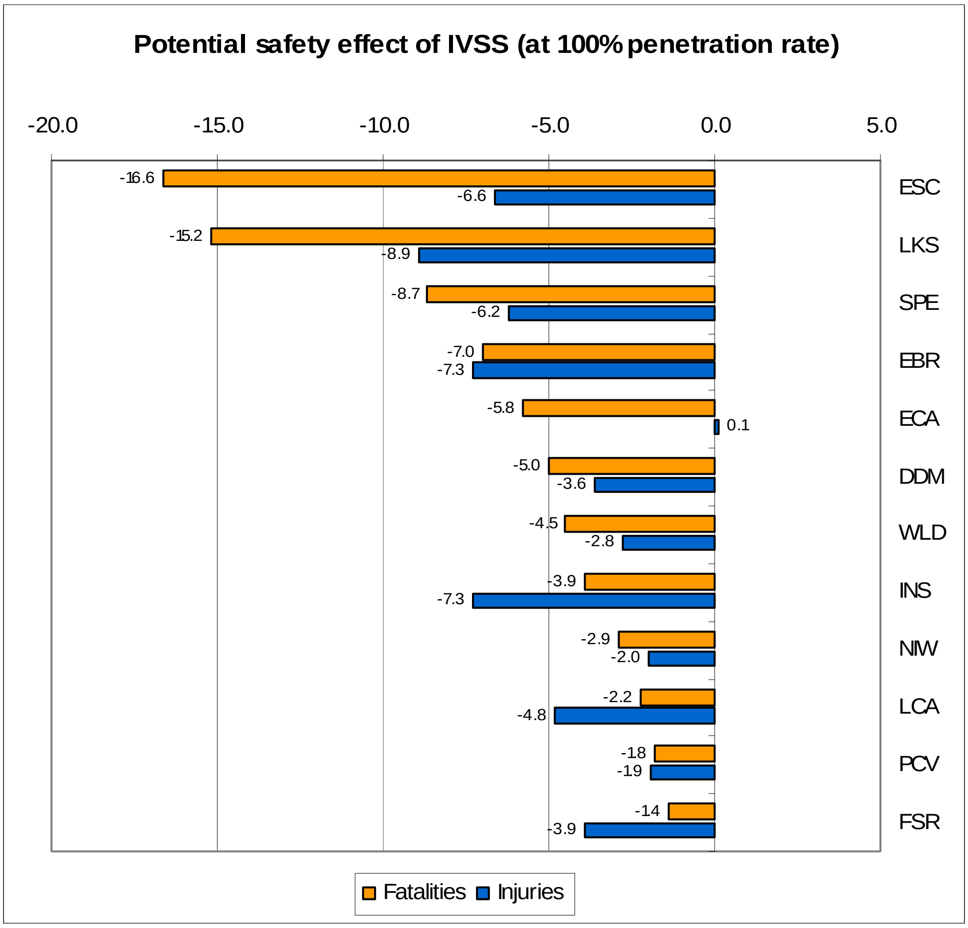
The potential reductions are in the range of 1.4–16.6% for fatalities. For injuries, the effects range from a very small increase in injuries (0.1%) for eCall to a decrease of 8.9% for Lane Keeping Support. Electronic Stability Control (ESC) has the highest potential safety impact, in terms of avoided fatalities, followed by Lane Keeping Support (LKS) and SpeedAlert (SPE). These systems are all aimed at several different collision types, and are reasonably to very effective in preventing these. LKS has the highest potential to reduce the number of injuries.

The Emergency Braking system (EBR) is not expected to have high impacts in 2020, but this is mainly due to the low penetration rate, as the system is assumed to have quite good potential to improve road safety. NightVisionWarn (NIW) and Driver Drowsiness Monitoring and Warning (DDM) have quite similar effects: both systems seemingly focus on a significant group of accidents but the systems' effectiveness to prevent these accidents was estimated to be limited. This can be because within the targeted group of accidents, the system is ultimately expected to affect only a small part of the accidents (e.g. NightVisionWarn cannot be expected to prevent the majority of accidents occurring in the dark), or there are unintended effects (modified behaviour, described by mechanisms 3–8) which reduce the total expected effect. Intersection Safety (INS) was assessed to be somewhat more effective, but the target accident group of fatalities is relatively small at the EU level, and therefore the system's safety potential to reduce fatalities is limited. The potential to reduce injuries is much higher.

Full Speed Range ACC (FSR) has the lowest potential impact on fatalities. This system targets only a small share of all accidents (but is expected to be quite effective in preventing those). This is also the case for Lane Change Assistance (LCA) and, to a lesser extent, for Pre-Crash Protection of Vulnerable Road Users (PCV).

eCall (ECA) does not prevent accidents and is relevant only for mitigating the effects of selected collision types. However, eCall has a high penetration rate in the 2020 high scenario, and thus still has a relatively high impact on the number of fatalities. However, as most of the fatalities are turned into injuries, and not many injuries are avoided, the system will result in a very small increase in the number of injuries.

Figure 4:. Potential safety effect (%) for the 12 selected IVSS if all vehicles would be equipped with the system. (Wilmink et al., 2008)



6. Socio-economic assessment

Results concerning the socio-economic assessment in CODIA are shown in Figure 5 for the high penetration scenarios covering the period 2005–2030. In the cost benefit analysis, the benefit side was dominated by the savings in accident costs followed by the savings in congestion costs due to reduced accident related congestion. Direct time costs were increased by all systems except for reversible lane control. The costs were dominated by the in-vehicle system costs as the infrastructure related investments were estimated to be quite modest up to 2030. Benefit to cost ratios are shown in Figure 6.

Figure 5: Benefits and costs for the deployment of four cooperative systems up to 2030. High scenario for market penetration.

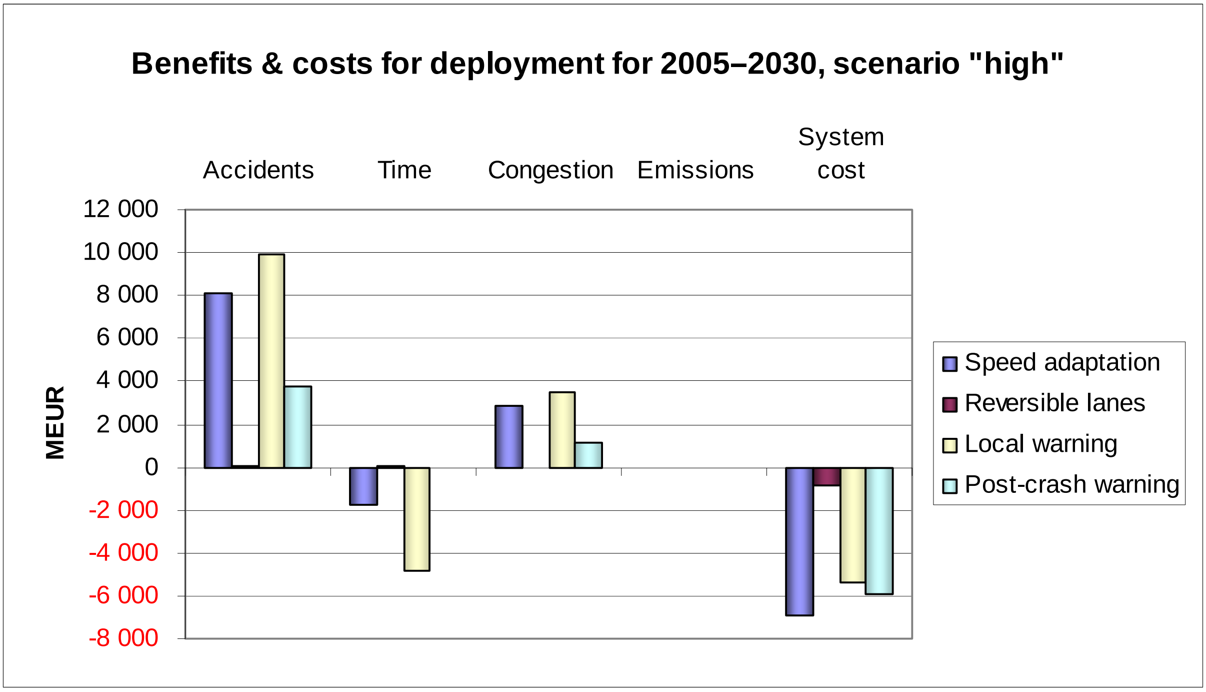
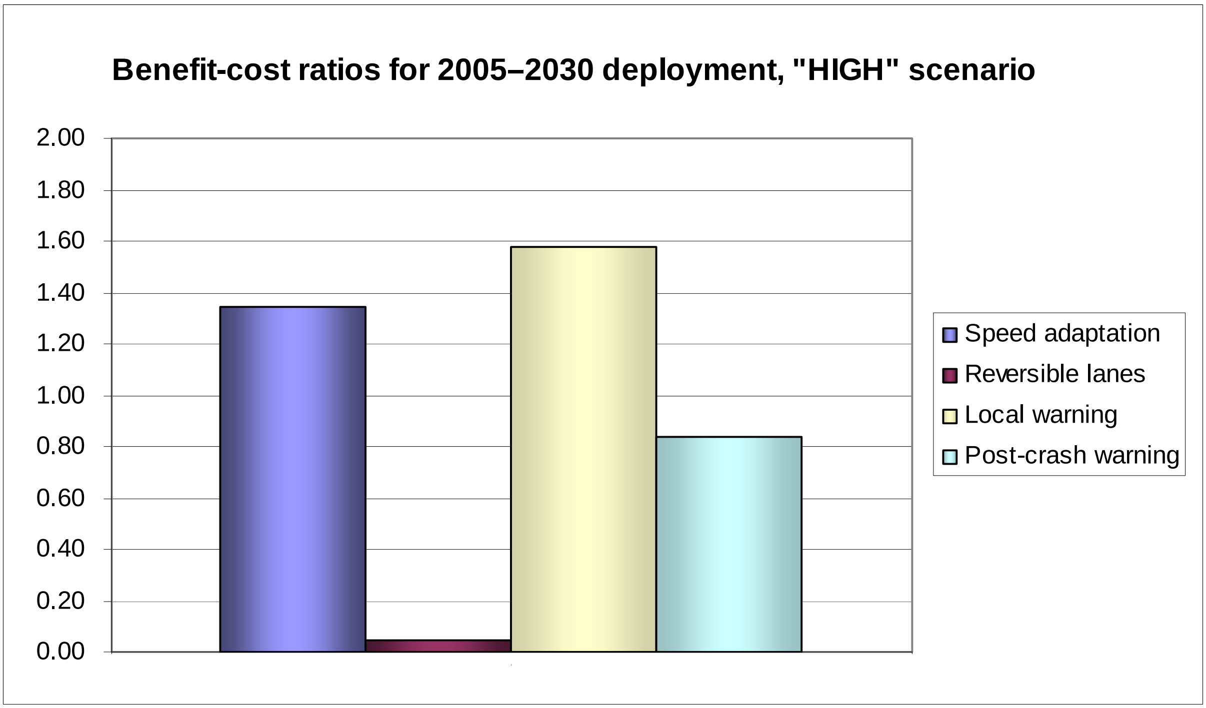


Figure 6: Benefit/cost ratios for the deployment of four cooperative systems up to 2030. High scenario for market penetration.



With regard to benefit to cost ratios, co-operative speed adaptation and local danger warning indicate socio-economic profitability. Post crash warning is not socio-economically profitable due to its modest safety impact. Reversible lane control is not profitable as there is a mismatch between the relatively high deployment costs and the small overall benefits. The overall benefits are small as the system is suitable only for a very small part of the European road network, even though on those few sections the system produces considerable benefits with regard to safety, congestion, journey times, and emissions. Intersection collision warning was not covered by the socio-economic assessment.

7. Discussion and conclusions

This paper has provided results of the impact and socio-economic assessment of the deployment of cooperative systems based on vehicle to vehicle and vehicle to infrastructure communications. These systems do not exist today in their cooperative form, and hence, the assessments have no basis of empirical results from real traffic. The analyses are based on a number of assumptions concerning the technical and functional features of the systems as well as their costs and deployment scenarios.

The vehicle penetrations and infrastructure coverage for the five systems used in the calculations are predictions with many uncertainties, even though the predictions are based on views of experts in and outside the CODIA and eIMPACT consortia. These uncertainties remain when the estimates have been transformed into fleet and vehicle mileage penetrations. Hence, all these figures are presented with two values: low and high, indicating the likely range of the penetration values.

Due to the uncertainties related to the data used for the assessments, the analyses have been attempted to present in a transparent manner. This enables quick updating of the results, when new evidence of the effects of the system in e.g. driver behaviour and traffic flow become available from the Field Operational Tests.

The assessments of the effectiveness of the systems with regard to the different impacts are utilising state of the art methods developed in eIMPACT and earlier projects, but also further enhanced and fine-tuned in CODIA.

The safety analyses demonstrated the importance to systematically study all impact mechanisms – several significant positive and negative impacts would have been missed if the indirect and unexpected impacts were ignored. In addition to this careful analysis providing the total effectiveness estimate, the results are dominated by the frequency of target conditions in the data (e.g. share of fatalities in junctions, share of injuries in adverse conditions); assumptions made on use and penetration of the systems; and finally, general development assumed in crash data for future years.

Some slight adjustments were made in CODIA into the safety assessment methodology. The impacts of mechanism 4 'indirect modification of non-user behaviour' and 5 'modification of interaction between users and non-users' were assumed to increase stepwise with the increasing fleet penetration until to 50%, and thereafter decrease and approach zero in full penetration when non users no more exist. In addition assumptions of use were made: some of the systems are applicable only for parts of the road network; for intelligent speed adaptation it was assumed that the users would have the system on 55% of time. Compared with many other systems intelligent speed adaptation provides repeatedly audio messages not connected to an obvious danger. Consequently, the messages can sometimes be experienced as annoying by the drivers.

In the cost benefit analysis, the benefits were dominated by reductions in accidents and their consequences, fatalities and injuries. The largest benefits were the savings in accident costs followed by the savings in congestion costs due to reduced accident related congestion. Direct time costs were increased by all systems except for reversible lane control. The costs were dominated by the in-vehicle system costs as the infrastructure related investments were estimated to be quite modest up to 2030.

The socio-economic assessment utilised the methods developed in earlier studies such as SEiSS and eIMPACT. The unit cost values for accident related congestion in earlier studies were found to be underestimated, and higher values were used in CODIA. As these costs play a major role in the assessments, further studies should be conducted to estimate the correct magnitude of congestion costs related to accidents of different type and severity.

It is obvious that the socio-economic feasibility of the systems will greatly rely on how economically the systems can be deployed in the vehicles and in the road infrastructure. The basic V2V and V2I communication components can be shared with a number of different cooperative functions, and this sharing is essential for economic reasons. It also seems likely that the systems will be deployed as both OEM and aftermarket or even nomadic systems. In the latter case, the costs will quite likely be somewhat lower due to the economies of scale and quick production cycles.

It should be noted that the studies assessed cooperative systems in comparison to a situation without any similar system supporting the driver or the network operator. The systems could also have been compared to a similar system without the cooperative element, such as a fixed speed limit based speed alert system in a navigator, infrastructure based reversible lane control or local danger and incident warning systems based on VMS (Variable Message Signs). Such comparisons would have made it possible to assess the benefit of the cooperative element of the system in isolation.

We have attempted to systematically assess the impacts and socio-economical profitability of a few cooperative systems. The methods used and further developed in the course of these studies should be utilised in further assessments of the cooperative systems. Our studies indicated many uncertainties not only in the vehicle fleet penetration and infrastructure coverage of the systems, but also in the expected driving and travelling behaviour of the users. Future studies should pay specific attention to investigating how these cooperative systems will change driver and traveller behaviour. Especially large uncertainties surround the impacts of these systems, where systems communicate and interact with other systems, on the interaction of the driver with other road users, his/her own vehicle and the traffic environment. These interactions are crucial for road safety and also for the function of the whole road transport system. Hence, future Field Operational Tests should provide special focus on the effects of the systems on driver interactions and behaviour.

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