Ex-ante assessment of the safety effects of intelligent transport systems

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Abstract

There is a need to develop a comprehensive framework for the safety assessment of Intelligent Transport Systems (ITS). This framework should: (1) cover all three dimensions of road safety—exposure, crash risk and consequence, (2) cover, in addition to the engineering effect, also the effects due to behavioural adaptation and (3) be compatible with the other aspects of state of the art road safety theories. A framework based on nine ITS safety mechanisms is proposed and discussed with regard to the requirements set to the framework. In order to illustrate the application of the framework in practice, the paper presents a method based on the framework and the results from applying that method for twelve intelligent vehicle systems in Europe. The framework is also compared to two recent frameworks applied in the safety assessment of intelligent vehicle safety systems.

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1. Introduction

The fast development of Information and Communication Technologies (ICT) during the last decades has led to a fast implementation of new applications and services in different domains. In transport, the application of ICT has led to Intelligent Transport Systems (ITS). Many such systems are already widely used, either as infrastructure based such as variable message signs, signal control, automated enforcement, motorway control systems, variable speed limits, and electronic toll collection, or as vehicle based systems such as antilock brake systems (ABS), electronic stability control (ESC), tyre pressure monitoring, adaptive cruise control, speed alert, alcohol interlocks and seat belt reminders. Some ITS systems are available also via nomadic devices (mobile phones, navigators, personal digital assistants (PDA), etc.) such as information and warning services as well as navigation. In addition to these “autonomous” systems relying on their dedicated sensors and communication systems, cooperative systems relying on communications between vehicles or between vehicles and the infrastructure are currently being developed. For definitions of these and many other ITS systems, see e.g. eSafetySupport (2009).

The potential of ITS has been widely recognised as a tool for achieving considerable gains especially in safety but also in efficiency and sustainability all over the world. This has led to initiatives and programmes to develop and deploy ITS systems, such as the Intelligent Car Initiative (CEC, 2006) and eSafety Forum (CEC, 2003) in Europe, Intelligent Vehicle Initiative (Hartman and Strasser, 2005) and Vehicle Infrastructure Integration programmes in the United States, and the Advanced Safety Vehicle and SMARTWAY programmes in Japan (Schulze, 2006).

To decide on investments on different ITS services, systems and information infrastructure, decision makers need the information on the impacts of ITS. To meet this demand, several databases are available (eSafety, 2008; U.S. DOT, 2008; TEMPO, 2008). Reviews of the safety and other effects of a number of ITS applications have been produced, among others, by Perrett and Stevens (1996), ETSC (1999), Öörni (2004), Kreiss et al. (2005), Vaa et al. (2007), Linder et al. (2007), the eSafety Forum (2007a), and Spyropoulou et al. (2008).

For existing systems, these reviews are helpful for the authority, industry and other stakeholder decision makers, although the empirical evidence available is patchy, covering only some aspects of the impacts. For deciding on investments for new systems on the basis of cost benefit analysis and other methods, the impacts need to be assessed based on other methods. Hence, there is a need to have a valid and comprehensive assessment framework, which covers all impacts of ITS, as well as a method to apply this framework in practice. This paper aims to provide such a framework and a practical tool with regard to the safety impacts of ITS. However, let us first explore the theoretical basis of traffic safety activities and safety measures as well as available safety frameworks.

2. What is traffic safety?

Traffic safety is usually regarded in terms of traffic “unsafety”, i.e. as the number of fatalities or injuries resulting from traffic accidents. Many researchers (e.g. Elvik and Vaa, 2004; Hauer, 1997; Kulmala, 1995) have defined traffic safety as the expected num-
number of fatally or otherwise injured persons of an entity in a unit of time. Here the entity can mean a road section, a junction, a driver or a group of drivers or a vehicle. It is imperative to note the word “expected” as the actual number of fatalities will fluctuate around the expected number in a way best described with a purely random distribution, often from the Poisson distribution family.

As Thulin and Nilsson (1994) showed, traffic safety has three primary dimensions of exposure, risk and consequence. Here exposure is measuring the magnitude of being exposed to accidents, usually expressed in person, ton or vehicle kilometres or hours travelled, or number of vehicles or vehicle kilometres passing though an entity. These three dimensions have a multiplicative relationship with regard to safety (Nilsson, 2004):

\[
E(\text{Fatalities}) = E(\text{Exposure}) \times \left( \frac{E(\text{Accidents})}{E(\text{Exposure})} \right) \times \left( \frac{E(\text{Injured})}{E(\text{Fatalities})} \right)
\]

This is illustrated in Fig. 1, where the volume of the rectangular box is the expected number of injured or fatalities:

As well illustrated and explained by Elvik and Vaa (2004) and complemented by Luoma (2007), there have been five major theories trying to explain road safety and road accidents: (1) theory of accidents as purely random events, (2) statistical accident theory and accident proneness theory, (3) causal accident theory as expressed in the in-depth case study approach to accidents, (4) systems theory and epidemiological accident theory and (5) behavioural accident theory.

The three last ones are currently being widely applied in road safety activities, and it is useful to highlight their starting points.

Causal accident theory was developed to identify actual causes of accidents by thoroughly investigating the events and circumstances that have resulted in accidents. The underlying assumption was that if the causes of the accidents were determined, countermeasures could be designed to prevent the accidents. One of the main findings repeatedly found everywhere was that 85–90% of accidents are caused by human factors (Hakkinen, 1978). However, the excessive focus on human aspects led to the question of why a human makes errors. More generally, the advanced applications of this theory concluded that accidents are typically multi-causal events and almost no accident involves a single factor that should be the focus of accident prevention. This resulted in an approach that concentrated on ordinary driver behaviour and what contributes to these unintended errors. The concept “system” saw the light of the day (Luoma, 2007).

Systems theories were designed in the 1950s as a counter-balance to accident proneness and accident causation theories. According to the main premise of systems theory, accidents are the results of maladjustments in the interaction between the components of complex systems. It is not possible to pick out any part of the road transport system as more crucial than others for its successful operation. Furthermore, there is no interest in causes or persons at fault. It is accepted that humans err, but it is essential why they make errors, what are the errors like, etc. In general, the technical components of the system are not adequately designed and matched to human capabilities (Elvik and Vaa, 2004).

Application of systems theory resulted in modifying the technical components of the road transportation system. Better roads and vehicles were designed in terms of human capabilities and limitations (e.g. channelisation of intersections, roundabouts, modern guide signing, daytime running lights, and many ergonomic aspects of vehicles). Many of these applications currently seem self-evident. Furthermore, safety research focused on the investigation of normal driver behaviour, requirements of safe behaviour, and searching for the best solutions from the viewpoint of road users (Luoma, 2007).

The behavioural theories as proposed by Elvik and Vaa (2004) for the next road safety paradigm attempt to describe how human risk assessment and human risk acceptance affect the accident involvement of road users. Luoma (2007) regards these theories as an elaboration of the systems theory rather than a new and different concept. Luoma (2007) views the transport systems involving road users, traffic environment, vehicles and control of the system as well as the interactions between the various elements. These interactions are forms of human behaviour containing sub-systems such as Perception – Information processing – Decision – Response Selection – Response Execution.

Today systems and behavioural theories are dominating road safety research, methodologies and deployment activities. Accident causation methods and tools based on the causal theory are also used. Typical application areas for these include in-depth investigation of accidents for identifying the contributing factors to accidents or pointing out the guilty or faulty parties in the accidents.

### 3. Effects of safety measures

Safety measures, or any measures undertaken in the transport systems, influence safety by affecting one or several of the factors contributing to any of the three dimensions of safety—exposure, crash risk or consequence. In the case of a safety measure, these factors tend to be the primary target of the measure. In addition to these “target factors”, the measure can also affect other factors related to the three dimensions of safety. If these other factors have an adverse effect on safety, their impact may totally or partly outweigh the positive effect due to the positive impact on the target factors. Usually the effects on other factors occur due to behavioural changes evoked by the measure and are described with the term “behavioural adaptation”, i.e. road users adapt their behaviour to various measures to a greater or lesser extent, but not necessarily to fully compensate for the measures. Probably due to the frequency of engineering based measures, the effect on target accident contributory factors is called “engineering effect” (Elvik and Vaa, 2004; Evans, 1991). This is illustrated in Fig. 2.

The behavioural adaptation can be explained more generally in terms of the utility theories (e.g. Little, 2002). These theories claim that individuals and thereby also road users behave rationally on the individual level and try to satisfy their own needs and preferences, aiming to maximise their utility. Road users derive utility naturally from not being injured in crashes, but also from reaching their destination on time, feeling comfortable, listening to their
favourite music, being able to utilise travel time to working, etc. The behavioural adaptation can also regarded to be primarily connected to the perceived risk of the drivers and the changes in the perceived risk brought about by the systems. Behavioural adaptation is thereby talked in terms of risk compensation (see e.g. Wilde, 1994).

Behavioural adaptation can exist in many forms and at all levels of driver (or more generally road user) decision making suggested by Michon (1985) i.e. strategic, tactical and operational. At the strategic level, behavioural adaptation can exist as changes in journey making, timing, mode choice and route choice, while at the tactical level, it can manifest itself in changes in lane choice as well as target speed levels and following headways. At the operational level, behavioural adaptation may affect, e.g. gap acceptance, situation awareness, alertness, speed choice, and manoeuvring. Most of the discussion has so far concentrated, however, only on the tactical and operational level behavioural adaptation.

Spyropoulou et al. (2008) review different ITS systems with regard to their direct and indirect (modification of driving behaviour as a consequence of system use). They point out user frustration and acceptance as crucial issues for system use and thereby effectiveness in addition to listing examples of behavioural adaptation. Cacciabue and Saad (2008) identified six parameters that characterise driver behaviour and, at the same time, the state of the art concerning behavioural adaptation to driver support systems. These parameters were: attitudes/personality, experience/competence, task demand, driver state, situation awareness/alertness, and intentions/goals. Bjørnskau (1994) proposed five hypotheses designed to explain road user behavioural adaptation to any road safety measures. These can be listed in the following way utilising Elvik (2002):

1. How easily a measure is detected
   If the road user detects a change in any element of the system, he or she may perceive this as a change in the level of risk. If sight distance along the road is increased, for example, most road users would probably perceive this as a gain in safety margin. On the other hand, if cars are equipped with collapsible steering columns, drivers would not detect it and might not even know it. Measures that introduce changes that are easily detected by road users are more likely to lead to behavioural adaptation than measures that they do not easily detect.

2. Antecedent behavioural adaptation to target factors
   If road users have already adapted their behaviour to the target factor, i.e. the safety related factor that the measure is meant to influence, the measure is more liable to behavioural adaptation than if such an adaptation has not taken place. Periodic inspections of private cars is probably more liable to behavioural adaptation than road lighting, because road users try to compensate for technical defects in cars by driving more carefully but they do not adapt their behaviour as much to reduced visibility at night by slowing down or being more alert.

3. Size of the engineering effect on target factors
   The greater the engineering effect, the greater the probability that there will be behavioural adaptation. For example, it is more likely that improving a car’s headlights will lead to behavioural adaptation when driving in the dark than when driving in daylight.

4. Whether or not a measure primarily reduces injury severity
   Measures which reduce the risk of being involved in an accident are more liable to risk compensation than measures which reduce the severity of injuries in a crash. For example, ESC should be more liable to behavioural adaptation than air bags.

5. Whether or not additional utility can be gained
   The road user will adapt his or her behaviour only if this results in higher utility. For example it is difficult to think of a behavioural adaptation to gates blocking the road partly or totally at railroad level crossings. For a vast majority of drivers, driving in a zigzag pattern between lowered gates is too dangerous to outweigh the benefits due to saved travel time.

4. Framework for the safety assessment of ITS

On the basis of the above, the framework for the safety assessment of ITS should: (1) cover all three dimensions of road safety—exposure, crash risk and consequence, (2) cover the effects due to behavioural adaptation in addition to the engineering effect and (3) be compatible with the other aspects of state of the art road safety theories.

A framework for assessing the road safety impacts that fulfils these requirements is the nine-point list of ITS safety mechanisms:

1. Direct in-vehicle modification of the driving task.
2. Direct influence by roadside systems.
3. Indirect modification of user behaviour.
4. Indirect modification of non-user behaviour.
5. Modification of interaction between road users.
7. Modification of modal choice.
9. Modification of accident consequences only.

The list is based on the ten-point list proposed by Draskóczy et al. (1998), which also included Modification of speed as the tenth mechanism. The list was at the time of its development mainly used to either illustrate all the possible ways in which ITS can affect safety or to check whether an evaluation plan covered the most relevant safety impacts for the system in question. For the purpose of an assessment framework, the mechanisms needed to be somewhat adapted, e.g., to eliminate overlaps and thereby the risk of “double counting”, to test the validity of any single mechanism, and to operationalise the mechanisms for assessment purposes.

The nine mechanisms as well as some current evidence of their existence are discussed below in more detail.

1. Direct in-vehicle 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). The criterion for this mechanism is that the effects are direct consequences of the use of the system; they are direct reactions to the system outputs and appear in few milliseconds or seconds. This mechanism covers both intended (e.g. decrease of speed to avoid a collision) and unintended (e.g. driver distraction) impacts.

Two studies provide typical examples of such effects. First, concerning speed alert via an active acceleration pedal, Várhegyi et al. (2004) found substantial reductions of average speeds and standard deviation of speeds. Second, according to the Dutch
Field Operational Test (FOT) of Adaptive Cruise Control ACC (Alkim et al., 2007), ACC use was linked to a decrease of short headways and the average achieved minimum headway was increased 0.2 s with ACC in busy traffic.

2. **Direct influence by roadside systems** mainly by giving information and advice. Without the possibility to control driver action or the vehicle directly, the impact of this influence is more limited than of the in-vehicle systems. In other aspects the impacts are similar as the ones described in mechanism 1.

Rämä (2001) showed that weather related speed limits accompanied with information and warning signs decreased the mean speed and the standard deviation of speed in adverse road weather conditions. The variable speed limits were most effective when slipperiness was difficult to detect. Under good conditions, when higher speed limits were allowed the mean speed increased moderately. Drivers seemed to follow the variable speed limits even more than the fixed speed limits. Roadside variable slippery warning signs caused a statistically significant decrease in driving speeds (Rämä and Kulmala, 2000) and as a part of a variable speed limit system, slippery road VMS also affected headways by reducing the percentage of very short headways (Rämä, 2001). Driver interviews at the same sites confirmed these impacts. In addition to the lowering of speeds in general and on curves, most drivers reported that they paid more attention to road surface conditions. On black ice conditions, some drivers also reported that they tested the slipperiness by braking carefully (Luoma et al., 2000).

3. **Indirect modification of user behaviour** in many, largely unknown ways. The driver will always adapt to the changing situation. This behavioural adaptation and will often not appear immediately after a change but may show up later and it is very hard to predict. The indirect modification is more long-term than the very direct, short-term reactions to the system in mechanisms 1 and 2. Long-term behavioural adaptation may appear in many different ways (for example, by reallocation of attention resources, by change of headway in a car following situation, by change of expectation of the behaviour of other road users). This adaptation may frequently be due to delegation of responsibility of the driving task partly or totally to the system, which the drivers have learnt to rely on.

As an example of such effects, Rudin-Brown and Parker (2004) found out in a test track study on ACC that drivers rely on ACC to keep their vehicle at a safe distance from a lead vehicle, and that ACC increased drivers’ response time to hazard detection and lane position variability. Ben-Yaacov et al. (2002) showed that drivers tend to overestimate their following headways, and consequently drive with short and potentially dangerous headways. Their results show that imperfect (reliability 60–95%) forward collision warning systems are useful for educating drivers to estimate headway more accurately, and that even after a relatively short exposure to the system, drivers were able to maintain safer headways for at least six months. Stanton and Pinto (2000) showed in their driving simulator study that a vision enhancement system improving vision in fog and in the dark would increase driving speeds and overtakings in situations of reduced vision, but that such behavioural adaptation was eliminated after a simulated failure of the vision enhancement system.

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). These effects are often evident at the traffic flow level.

Evidence of this has been obtained from Swedish studies on speed alert in the city of Umeå with approximately 4000 equipped vehicles. Those studies indicated that other road users were also affected by speed alert, i.e. they also lowered their speeds due to the equipped road users reducing their speeds (Biding and Lind, 2002).

5. **Modification of interaction between road users**. ITS will change the communication between equipped road users. This change of communication may also 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.

Evidence from a positive change in interaction can be found in the Swedish trials on speed alert. The drivers of equipped vehicles reported a considerable increase in attention towards unprotected road users, although only some observations confirmed this. The expected compensatory behaviour of not stopping at pedestrian crossings to make up for lost time was not evident, except for stressed bus drivers (Biding and Lind, 2002; Várhegyi et al., 2004). Evidence from a negative change of interaction is presented by a simulation study on a collision warning system by Zheng et al. (2005). They showed that a host vehicle equipped by the system and reacting to a collision warning could be more dangerous than 99.7% of vehicles braking normally. The result implies an increased risk of a second collision with a follower if the host vehicle decelerates hard to avoid a collision following a warning from the system (Zheng et al., 2005).

6. **Modification of road user exposure by for example information, recommendation, restrictions, debiting.** This mechanism covers only changes in the amount of travelling, i.e. whether the road user decides to make more or less, or longer or shorter, trips due to the system. This is an important mechanism for the safety effects as changes in exposure affect the expected number of all crashes, injuries and fatalities as shown by, e.g., Fridström et al. (1995).

Such evidence exists from such applications, where this sort of effect was also one of the targets i.e. part of the engineering effect. Vonk et al. (2007) estimated an average 16% decrease in travelled kilometres due to the use of dynamic navigation system, when driving to a previously unknown destination. Centralised route planning in fleet management has been shown to decrease commercial vehicle mileage by 18% (U.S. DOT, 2005). Empirical evidence of changed exposure as a behavioural effect is not available, but this is probably only due to the fact that no one has studied it. It is reasonable to assume that systems, which make driving easier in adverse conditions, will encourage at least some of the drivers normally too uncomfortable to drive in such adverse conditions to use their car in such conditions with the support of the system. The results of Assum et al. (1999) provide an example of such an effect. Specifically, Assum et al. (1999) showed that road lighting increased travelling in the dark especially for the elderly. Such an effect would also be likely with a well-working night vision system.

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.

Evidence of such impacts exists for systems, which aim to modify modal choice as their engineering effect. A public transport information system with real-time bus and tram arrival time displays at stops together with signal priorities for public transport increased passengers using public transport by 1% in Helsinki. This was estimated to mainly be passengers formerly using walking or cycling (Lehtonen and Kulmala, 2002). An internet public transport journey planner for a large urban area was...
Table 1
The safety assessment framework by road user decision level, safety dimension and safety effect type. Black colour indicates that the mechanism typically focuses on that aspect, grey means relevance but no focus on the aspect.

<table>
<thead>
<tr>
<th>Road user decision level</th>
<th>Safety dimension</th>
<th>Effect type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic</td>
<td>Exposure</td>
<td>Engineering</td>
</tr>
<tr>
<td>Tactical</td>
<td>Crash risk</td>
<td>Behaviour</td>
</tr>
<tr>
<td>Operational</td>
<td>Consequence</td>
<td></td>
</tr>
</tbody>
</table>

1. Direct in-vehicle modification of the driving task
2. Direct influence by roadside systems
3. Indirect modification of user behaviour
4. Indirect modification of non-user behaviour
5. Modification of interaction users/non-users
6. Modification of exposure
7. Modification of modal choice
8. Modification of route choice
9. Modification of accident consequences only

Assessed by Laine et al. (2003), who estimated on the basis of user survey an increase of 3% in the use of public transport among the users of the service. A half of this increase was due to modal shift from private car use and the other half from bicycling or walking. It is also possible that the equipment of cars with a system increasing the safety, comfort and security or reducing the expected travel time of the driver will make car driving more attractive resulting in a modal shift from, e.g. public transport to car use.

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. Note that route changes also affect exposure, and the exposure changes due to the route changes can be taken into account either under this mechanism or mechanism 6.

Dynamic navigation and route guidance systems aim to guide the users to their destination via the quickest route, which will result in route choice modifications. The TravTek route guidance system helped drivers to avoid congestion, and thereby the drivers used slightly longer routes on lower class roadways and, as a result, travel time remained about the same (Imman and Peters, 1996). A dynamic traffic information and route guidance system in Minnesota diverted drivers from congestion resulting from incidents to alternative routes (Booz-Allen and Hamilton, 1997).

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.

Several systems have been shown to affect safety via this mechanism. To give one example, the expected impacts of the European automated in-vehicle emergency call system, i.e. eCall, were studied on the basis of the case reports of road accident investigation teams in Finland. In all, the eCall system was estimated to be able to reduce 5–10% of motor vehicle fatalities in Finland. In 95% of the cases of reduced fatalities, the consequences would change to injuries requiring further hospital and other treatment, and in the remaining 5%, to injuries requiring no further treatment at all (Sihvola et al., 2009).

As evident from above, these mechanisms are valid in the sense that empirical evidence of the existence of each of them is available. Table 1 attempts to illustrate to which degree the effects of the framework focus on the different road user decision levels, safety dimensions and the main effect types.

Table 1 shows that the framework covers the road user decision making on all levels—strategic, tactical and operational while also covering all three safety dimensions of exposure, crash risk and consequence. Note that the mechanisms 1–5 also cover consequences due to the mechanism related changes in driving speeds and thereby collision speeds, which have a major impact on the consequences of road crashes. Mode and route choice affect mostly crash risk, but also exposure. For example, use of public transport with low expected crash risk often increases kilometres travelled via longer routes and additional walking (with less passenger protection in crashes). Moreover, use of motorways may increase journey length in kilometres although, in comparison with two-lane roads, crash risks are generally lower and the consequences of run-off-the-road accidents via good roadside protection facilities are smaller.

Despite the attempt to provide mutually exclusive mechanisms, some specific effects of ITS could be included into more than one effect mechanism. When using the framework in practice, it is important that no double-counting takes place and each specific effect is included in the assessments only once. To our experience, all of the nine mechanisms are useful and necessary for considering all known effects of the system.

5. Application of the framework

This framework was first applied within the EU project eIMPACT, which carried out the socio-economic assessment of 12 intelligent vehicle safety systems (IVSS) (Wilmink et al., 2008). Some of the 12 systems are already available on the market, whereas most of the systems are not, at least in the configuration studied.

The method was applied to accident data for 25 EU member states provided by the TRACE project (Page and Stanzel, 2006). The accident data was organised according to six background variables:

2. Collision type (collision on the road with pedestrian, collision on the road with all other obstacles, collision besides the road with pedestrian or obstacle or other single vehicle accidents, frontal collision, side-by-side collision, angle collision, rear collision, other accidents with two vehicles).
3. Road type (motorway/rural/urban).
4. Weather conditions (normal/adverse).
5. Lighting conditions (daylight/night).
6. Location (intersection/not intersection).

These background variables were chosen due to their availability in the accident statistics of most European countries. However, the assessment framework does not imply any restrictions to the variables used.

The assessment of each system was based on the proposed safety assessment framework, and used as its foundation the background variable among the six above, for which most reliable evidence of behavioural based safety effects were available. This background variable was called the basic variable for each system. In most cases, behaviour related evidence would be and was available only concerning some specific situation, and the total effect estimate could be then be linked to this specific situation or basic variable category. In many cases the basic variable was the collision type; it was, e.g. known based on previous field tests and literature how effective the system has been estimated to be for different collision types in a certain area or country in Europe. Also other factors might be most relevant, e.g. road type or location. In fact, all background variables, except vehicle type, were chosen as basic classifying factor at least for one safety function (Kulmala et al., 2008).

For each variable, the effect was weighed for different variable categories, e.g. it was assumed that the IVSS in question would be more effective on rural and urban roads than on motorways. In this consideration, the focus was on the effectiveness of the system, it is how powerful the system would be to affect different accidents in defined circumstances, not on the frequency of the accident type in question. In addition, the weights of the effect for a background variable could vary by mechanism, e.g. there might be some reason to weigh the effect according to the road type in direct effects (mechanism 1) but not in exposure effects (mechanism 6).

A specific calculation tool (Excel workbook) was created to handle the efficiency coefficients for all relevant mechanisms. The tool included one Excel worksheet for each background variable. The inputs for each worksheet were:

- Expert estimates for the average effects (AE) for each mechanism (AE[mi], AE[m2], ..., AE[m0]).
- Expert estimates of efficiency coefficients (EC) in per cent for each mechanism and each variable category [EC(mi; Vj1), EC(mi; Vj2), EC(mi; Vj6;1), EC(mi; Vj6;2), EC(mi; Vj6;3), EC(mi; Vj6;4), EC(mi; Vj6;5), EC(mi; Vj6;6)].
- The total number of accidents/fatalities or injuries (accident data).
- The proportion of accidents (PA) in each variable category based on the accident data set in question [PA[Vj1], PA[Vj2], PA[Vj3], ..., PA[Vj6;1], PA[Vj6;2]].

We assigned first the expert estimates efficiency coefficients EC in percent for the categories of the basic variable for each mechanism based on the existing evidence of the effects of the system on behaviour and/or road crashes. On the basis of these estimates, we calculated the average effects [mi] for each mechanism i. For other variables, we estimated the relative effectiveness of the system in each category, and then the tool computed a calibration factor for each background variable which took into account the frequency of accidents in the variable categories and the average effect for the mechanism. This was done to ensure that the magnitude of the total average effect estimate would not be biased due to differences in the different accident distributions by variable category in the data from different regions and countries. On the other hand, this procedure was used in some cases in checking the estimates for data from different countries and comparing these to any existing empirical evidence from those countries. In that way, the data was used to check the plausibility of the first estimates, it is to validate the estimates. The formulas were as follows (Kulmala et al., 2008):

The overall efficiency coefficients (OEC) for each category k of variable j (collision type, etc.) were computed based on values calculated for individual mechanisms by using the efficiency factors $EF = EF + 1 + EC/100$. This was done by

$$
OEC[Vj,k] = 100 \times \frac{EF_{new}}{EF_{ori}} \times \frac{EC_{ori}}{EC_{new}} - 1
$$

The first estimate of the overall total effect for the accident data set in question can always be calculated as the sum

$$
\sum_{k=1}^{K} OEC[Vj,k] \times PA[Vj,k] = \sum_{k=1}^{K} \left(1 + \frac{EC_{ori}}{EC_{new}} - 1\right) \times PA[Vj,k]
$$

The overall efficiency coefficients or proposed factors were used in the final calculations when the accident data was multiplied with the corresponding factors. In order to estimate the effects in a number of countries with different types of conditions and circumstances, it was necessary to select one accident case (e.g. intersection accidents), where the percent effect would be the same in all countries or regions. Therefore, for each system a basic case, i.e. a category of the basic variable was chosen. For this case and other categories for the specific variable, the calibration factor was always set to 1. Then the safety effect was first calculated on the basis of this variable and all the other variables were calibrated in relation to this estimate. Note that the safety effect will because of this differ between different data sets depending on the distribution of accidents according to this particular variable (Kulmala et al., 2008).

For the final effect estimates the accident data was organized on the basis of the same six background variables but this time so that each accident data cell corresponded to one category of each six variables. For each cell, the data was multiplied with the effect coefficients corresponding with these categories. This assumes that the background factors are independent of each other and their overall effect could be estimated by multiplying the effect factors. Despite the use of the calibration factors to minimise the data set related bias, the dependencies in the accident data set affect the total effect of the system. The magnitude of this is evident as the difference between the “first estimate” calculated with the analysis tool and the summed up effect from the large accident table. Note that the first effect estimates were provided for 100% fleet penetration. The effect estimates were multiplied by the estimated fleet mileage penetrations. In general, a linear development of the effects for different penetrations was assumed (Kulmala et al., 2008).

Some estimates were more based on expert opinion than others because it was always not easy to find evidence from literature, or
Table 2

Effects of 12 Intelligent Vehicle Safety System (IVSS) on the number of road fatalities in 25 EU member states in case of 100% fleet penetration by safety mechanism (Wilmink et al., 2008).

<table>
<thead>
<tr>
<th>System</th>
<th>Effects of IVSS on the number of road fatalities by safety mechanism (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td></td>
</tr>
<tr>
<td>Electronic stability control ESC (corrected by author)</td>
<td>−21.1</td>
</tr>
<tr>
<td>Full-speed range adapt. cruise control</td>
<td>−2.1</td>
</tr>
<tr>
<td>Emergency braking</td>
<td>−7.2</td>
</tr>
<tr>
<td>Pre-crash protection for vulnerable road users</td>
<td>−2.5</td>
</tr>
<tr>
<td>Lane change assistance</td>
<td>−2.3</td>
</tr>
<tr>
<td>Lane keeping Support</td>
<td>−17.7</td>
</tr>
<tr>
<td>Night vision warning</td>
<td>−6.9</td>
</tr>
<tr>
<td>Drowsiness monitoring/warning</td>
<td>−7.9</td>
</tr>
<tr>
<td>Emergency call eCall</td>
<td>−5.5</td>
</tr>
<tr>
<td>Intersection safety support</td>
<td>−8.6</td>
</tr>
<tr>
<td>Wireless local danger warning</td>
<td>−3.1</td>
</tr>
<tr>
<td>Speed alert</td>
<td>−5.5</td>
</tr>
</tbody>
</table>

The safety mechanisms are:
(1) Direct in-vehicle modification of the driving task.
(2) Direct influence by roadside systems.
(3) Indirect modification of user behaviour.
(4) Indirect modification of non-user behaviour.
(5) Modification of interaction between users and non-users.
(6) Modification of exposure.
(7) Modification of modal choice.
(8) Modification of route choice.
(9) Modification of accident consequences only.

the evidence was not complete. For these estimates a range was provided. Specifically, the expert opinion was made in addition to the most probable value also for a positive and negative scenario to reflect the level of uncertainty in the expert judgements. Furthermore, because it is acknowledged that expert judgements are typically higher than empirical observations, an attempt was to make the expert judgements as conservative as possible (Kulmala et al., 2008).

The magnitudes were calculated separately for individual systems, but the method can and was also applied to estimate the effects of an integrated system containing the functionalities of two systems (Kulmala et al., 2008).

Detailed results of the safety assessments of each system can be found in the eIMPACT deliverable by Wilmink et al. (2008) reporting the results of the impact assessment studies. An overview of the results is given in Table 2. Note that the figures are the most likely estimates of the safety effects of the systems in EU25, i.e. the 25 European Union Member States in 2005. The estimates take into account the national accident statistics and their distribution according to the six background variables. Hence, they are not directly comparable to the effects estimated for a single country or the meta-analyses that have been carried out for a number of systems relying on effects studies from one or more specific countries.

6. Relevance of the safety assessment framework for ex-post evaluation

The safety framework proposed has so far only been utilised in ex-ante assessment of in-vehicle safety systems. The framework

Table 3

Results and assumptions of five recent studies on ESC of the case-control type.

<table>
<thead>
<tr>
<th>Study</th>
<th>Estimated ESC effect</th>
<th>Assumption of crash type not affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dang (2004)</td>
<td>Effects concern USA</td>
<td>Multiple vehicle crashes</td>
</tr>
<tr>
<td></td>
<td>Single vehicle crashes of passenger cars: −35%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fatal single vehicle crashes of passenger cars: −30%</td>
<td></td>
</tr>
<tr>
<td>Lie et al. (2005)</td>
<td>Effects concern Sweden</td>
<td>Rear-end crashes on dry road surfaces</td>
</tr>
<tr>
<td></td>
<td>All injury crashes except for rear-end crashes: −17%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All serious injury/fatal crashes except for rear-end crashes: −22%</td>
<td></td>
</tr>
<tr>
<td>Kreiss et al. (2005)</td>
<td>Effects concern Germany</td>
<td>Accidents caused by turning off the road/or by crossing the road (by a pedestrian)</td>
</tr>
<tr>
<td></td>
<td>Driving accidents (caused by the driver's losing control of his vehicle due to not adapted speed or misjudgement of the course or the condition of the road, etc): −32% (all) and −56% (fatal)</td>
<td></td>
</tr>
<tr>
<td>Page and Cuny (2006)</td>
<td>Effects concern France</td>
<td>20 specific crash types where the function of the driver of the case vehicle would not have been braking or recovering from loss of control, e.g. car reversing and hitting a pedestrian, parking or parked car, car making a left turn or a right turn, car making a U-turn or car crossing the road, car-to-vehicle accidents at junctions, etc.)</td>
</tr>
<tr>
<td>Frampton and Thomas (2007)</td>
<td>Effects concern UK</td>
<td>Case vehicle manoeuvre: Reversing/Parked/Waiting to go ahead but held up/Stopping/Starting/Waiting to turn left/Waiting to turn right</td>
</tr>
</tbody>
</table>
appears to be covering all major ways in which ITS can effect road user behaviour and thereby road safety. Hence, it should also be applied to ex-post evaluation, especially when sufficient accident data is not available to quantify the effects in terms of changes in the numbers of fatalities, injured persons and road crashes. Even in the case of availability of accident data, the framework could be highly useful. Let us take the example of ESC that stabilises the vehicle and prevents skidding under all driving conditions and driving situations within the physical limits by active brake intervention on one or more wheels and by intelligent engine torque management (eSafety Forum, 2007a).

Most of the studies carried out so far (for review, see eSafety, 2008) have relied on the accident causation analysis approach by assuming that ESC only affects certain accident types and has no impact on other accident types. The estimate will then depend on the assumptions made. Therefore, the synthesis of such estimates with the help of, e.g. meta-analyses should be carried out with caution.

Table 3 sums up the main results and assumptions of recent case-control studies on ESC effectiveness. In addition to these, a number of before and after studies have been made (see e.g. Erke, 2008). Table 3 shows that the assumptions vary quite a lot between the different case-control studies selected with regard to which crashes would not be affected by ESC. Yet these assumptions are extremely important as they directly influence the estimate of the ESC effectiveness. If ESC also decreases the control type of crashes, the estimated crash reduction due to ESC is too low, and if ESC increases the control crashes, the estimated reduction is too high.

It is worth noting that recent studies indicate behavioural adaptation for ESC. Specifically, Rudin-Brown et al. (2009) concluded that the behavioural adaptation of certain drivers is likely to be driving faster, being more likely to drive in adverse weather conditions, driving faster in adverse weather conditions, and driving more aggressively. More than half of all ESC drivers in the Canadian sample erroneously believed that ESC will allow them to stop faster when necessary. According to Vadeby et al. (2009), Swedish car drivers consistently stated that they were more likely to take a risk when they thought they had ESC in their vehicle than when they did not.

Let us explore these assumptions with the help of the safety assessment framework proposed. It is reasonable to assume that at least the safety mechanisms 1, 3, 4, 6, 7 and 8 are relevant for ESC. The possible effects are given below.

1. Direct in-vehicle modification of the driving task—ESC prevents the driver from loss of control of the vehicle in many situations, and this would especially reduce the risk of running off the road accidents as well as head on collisions.

2. Indirect modification of user behaviour—drivers with ESC could use higher speeds and shorter headways relying on ESC to maintain the controllability of the vehicle in any case. The effect is probably highest in slippery conditions and in situations with increased risk of loss of control such as in curves, but might also appear in other conditions to some extent.

3. Indirect modification of non-user behaviour—drivers following a vehicle equipped with ESC might imitate the behaviour of the equipped vehicle and, e.g., in slippery conditions drive into a curve with higher speed that they would normally do.

4. Modification of user exposure—some drivers might drive more on slippery road conditions with ESC in comparison to when they without ESC would not have dared to drive unless necessary.

5. Modification of modal choice—as in the previous case, in adverse conditions travellers without ESC would use taxi or collective transport whereas with ESC they might use their own car.

6. Modification of route choice—some drivers might in adverse weather conditions dare with the assistance of ESC utilise also smaller roads with less effective winter maintenance.

All studies in Table 3 concentrate on assessing the effects of mechanism 1. Loss of control situations also often end up in vehicles diverting not directly off the road but also or at first to the lane used by opposite direction traffic, head on collisions are reduced by ESC as shown by e.g. Erke (2008) in her meta-analysis. Hence, the use of multiple vehicle accidents as such as a control is not appropriate. Mechanisms 4, 6, 7 and 8 probably have substantial effects only in such situations and countries, where slipperiness is very frequent. Hence, the choice of dry road surface conditions for the control case in the Swedish study by Lie et al. (2005) should control for these mechanisms. The effects of this mechanism on the German, French and UK results in Table 3 may result in a quite small bias in their results.

Mechanism 3 is the most crucial one for these studies. If this type of behavioural adaptation also occurs in other than slippery conditions or at curves, drivers of ESC-equipped vehicles could also use higher speeds and shorter headways in all conditions, also e.g. on dry road surfaces and when approaching junctions. This would result in biased estimates in all other studies here than that of Frampton and Thomas (2007).

ESC undoubtedly fills out four of the five hypotheses for behavioural adaptation, i.e. there is a antecedent behavioural adaptation to target factors at least towards driving in slippery conditions, the size of the engineering effect is very large, the measure aims specifically at reducing crash occurrence and not severity, and additional utility can be gained via reduced time consumption. However, there has been some doubt about one of the five hypotheses, i.e. how easily ESC is detected. One of the studies of Table 3, that of Page and Cuny (2006), in fact addresses this issue and disregards the relevance of behavioural adaptation for ESC by referring to a result from Bosch indicating that only 30% of drivers with ESC know of its instalment in their vehicle. At the same time, results on ESC effectiveness and campaigning to raise user awareness of the benefits of ESC (eSafetyAware, 2007) have increased the notability of ESC and thereby also the likelihood of behavioural adaptation. In the recent Canadian study of Rudin-Brown et al. (2009), (63)% of drivers of ESC equipped vehicles knew of their vehicle having ESC, while 8% of drivers of vehicles not equipped with ESC thought their vehicle had ESC.

7. Discussion

7.1. Validity of the framework

The safety assessment framework proposed and the related practical safety impact estimation method presented above offer a comprehensive way to explore and estimate the safety effects of ITS.

The framework and method cover all dimensions of road safety, also exposure or the amount of travelling, which is frequently overlooked in the safety assessment studies. Exposure is a crucial safety dimension as it affects the number of fatalities, injuries and crashes for all vehicle types and not just for the one accident type of situation, which the system is targeting. The numbers of fatalities, injuries and crashes can be expected to change approximately in direct proportion to changes in exposure. Hence, even small increases in exposure can compensate for large percent reductions of crashes of an infrequent type.

The assessment framework is based on the systems and behavioural theories widely used in current road safety research. Thereby, the framework also covers the well-known behavioural
adaptation. Unfortunately, actual studies on behavioural adaptation are few, and many of them have been made in driving simulators. As many forms of behavioural adaptation will manifest themselves after long time use of the system, the best way to study that would be via long-term observation of road user behaviour in real traffic. For this purpose, the current setting up (see e.g. eSafety Forum, 2007b) of large scale field operational tests for ITS systems and naturalistic driving studies are very useful.

7.2. Comparison with other frameworks

Several safety assessment frameworks have been proposed and utilised in various studies. Two of the more recent studies developing such frameworks are discussed shortly below.

The SEISS study (Ablele et al., 2004) proposes a general framework and methodology for the socio-economic assessment of intelligent vehicle systems. For the safety assessment, the study recommends a method primarily based on time correlation. The time correlation is explained as “The systems performance should lead to an earlier information, better car stability, faster breaking or fewer driving faults. These systems can therefore be represented by time gains or contrary, time losses. Depending on the systems (interaction), the time gained or lost can be added or subtracted. The effort cannot exceed the time slot. The time factors are speed-dependent...It is difficult to correlate some IVSS to time. This remains the case for ABS (ensuring steerability while braking), ESP (preventing loss of traction through braking of specific wheels) and Safe (Adaptive) Speed (which limits the maximum speed to the physical limits of the vehicle combined with the specific road conditions). The mechanism for these functions is a so-called Loss Of Control (LOC) scenario. Because of its high relevance in accident causes the LOC scenario must be considered in the model and modelled separately due to its time independence...Time gains will lead to a reduction in collision probability. No time gain translates into normal accident patterns or accidents occurring without the use of the specified IVSS. Additional reaction time for the car or the driver adds to the time gain and reduces the probability of a collision” (Ablele et al., 2004).

The SEISS study utilises the time correlation approach to estimate the changes in crash risk as well as consequence, but does not cover the exposure element. To determine the accidents, which are influenced, the accident causation approach is used. This means that the assessment is focussed on estimating the engineering effect as comprehensively as possible an other potential effects are excluded from the analysis.

The TRACE project aims to develop further the etiology (i.e. analysis of the causes) of road accidents and injuries, and the definition of the real needs of road users deduced from accident and driver behaviour analyses as well as assesses the most promising intelligent vehicle systems and solutions with regard to their safety impact (Page and Stanzel, 2006). In order to carry out the safety assessment, TRACE first assesses the “potential proportion of accidents that could be avoided and the potential of accidents whose severity could be reduced” called a priori effectiveness, and then “the actual proportion of accidents that could be avoided or whose severity could be reduced...once the cars are equipped” with the system, called a posteriori effectiveness (Karabatsou et al., 2007). The terms ex-ante and ex-post could also be used instead of a priori and a posteriori, respectively.

The a priori effectiveness is assessed by six methodologies (Karabatsou et al., 2007): (a) target population times efficiency approach, (b) automatic case by case analysis within database, (c) case by case analysis, dedicated software, integrated approach, (d) case by case analysis, dedicated software modular approach, (e) analysis of selected in-depth cases and (f) artificial neural networks. These effectiveness assessments are modified with the help of human needs fulfilment analysis. This analysis covers the functional driver’s needs (need as a counterpart of human function failure, e.g. if a driver has not seen a crucial element in a traffic situation, there is a perception need) as well as the conditions, under which these needs to be fulfilled (Karabatsou et al., 2007).

The a posteriori effectiveness is to be assessed by starting with the identification in the national data bases of accident involved cars for which it is possible to determine the equipment of the car with the studied in-vehicle system or safety function. The next step is to identify the accident situations for which it can be determined whether to system or safety function is pertinent or neutral. The assessment concludes in the calculation of the relative risk of being involved in a safety function pertinent accident for safety function equipped cars versus unequipped cars, divided by the relative risk of being involved in a safety function neutral accident for safety function equipped cars versus unequipped cars (Page et al., 2007).

The study and its methods indicate that the assessment is focussed on engineering effects concerning crash risk and consequence. The study makes a reference to risk compensation. However, it does not address it explicitly in the assessment methodology.

Both of the studies above and many other safety impact assessment studies are utilising the accident causation approach. That approach and related methodologies might be suitable for studying the engineering effect of a system, i.e. the effect on the risk factors or accidents, towards which the system is targeted. In fact, methods developed for assessing the magnitude of the engineering effect have been developed in an impressive manner in the past decade (see e.g. Karabatsou et al., 2007). However, the accident causation approach is ill suited to cater for a systematic assessment of behavioural effects or effects on exposure. In addition, the accident causation approach is not designed to consider effects at the traffic flow or transport system level, in general. Nevertheless, the use of the accident causation approach and related methodologies are to be recommended for the parts of direct in-vehicle modification of the driving task (mechanism 1) and modification of accident consequences (9).

7.3. Application of the framework in the future

The mechanisms and method have been developed for the ex-ante safety assessment of ITS, but they are suited also for the ex-post safety assessment of ITS. The framework can also be utilised in ex-post accident studies on ITS effectiveness as a checklist to ensure that all possible safety relevant impacts are considered in the study method and design. In this paper, such an analysis was carried out in a small scale for five studies on ESC effectiveness.

As we today know little about some effect mechanisms, the framework will result at best in a mix of a few empirically tested quantitatively quite reliable figures and a some expert judgements aggregated into a total effect estimate or a range of values for the most likely effect. Some researchers would like to stick to reporting only empirically tested figures, and refer to the other mechanisms only verbally or qualitatively. However, there are many important arguments for including the expert judgements in the calculations when we do not have specific empirical results for some relevant effects of a system. First, their inclusion will make the users of the safety assessment results more aware of the mechanism. Second, it is easy to replace the expert judgement based estimates with empirically tested figures when such become available from e.g. field operational tests. Third, the quantitative estimates are required for socio-economic assessments, which are a prerequisite for making decisions on the deployment of the systems. Fourth, the assessment framework ensures the transparency of the estimates made. Nevertheless, even the expert judgements should always be based on empirical studies on how different types of systems affect driver behaviour and thereby road safety.
The framework can be applied to any accident data, which is disaggregated according to background variables relevant for the safety effects of the systems studied. Such background variables are, for example, crash type, road type, vehicle type, etc. Naturally, accident data with all relevant variables will not usually be available, but even the availability of a data disaggregated according to some relevant variables is sufficient. The use of the framework facilitates the use of all available empirical evidence on the effects of a specific system or similar in different conditions as described by the background variables used in disaggregation. The safety impact estimates of the system in the country or region in question will reflect the actual conditions of the country or region. Thereby, the estimates are likely to be more accurate than those provided by e.g. meta-analyses based on evidence from other countries, where the conditions differ from the country or region in question.

Many of the mechanisms are closely linked to one another, and could be combined. This could hold for mechanisms of direct driving behaviour modification (1–2), indirect driving behaviour modification (3–5), and travel pattern modification (6–8). However, as the purpose of the framework is also to remind its users of and illustrate the types of different possible effects of ITS systems, all nine mechanisms are kept for time being.

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