Simulation-based evaluation of safety performance of Intelligent Vehicle Safety Systems

Constantinos Antoniou\textsuperscript{1} and Haris N. Koutsopoulos\textsuperscript{2}
\textsuperscript{1}National Technical University of Athens, Greece
\textsuperscript{2}Northeastern University, USA

Abstract
A number of systems, referred to as Intelligent Vehicle Safety Systems (IVSS) or Advanced Driver Assistance Systems (ADAS), are currently under development to enhance the driving task and assist drivers in avoiding collisions. In addition to the research that is necessary to develop the required technology associated with these systems, equally important is the understanding of the safety benefits that may be realized through their introduction. The objective of this research is to present a comprehensive framework for simulation-based evaluation of the safety performance of IVSS. Both the expected reduction of collisions, as well as the potential reduction in their impacts are of interest. A methodology for the simulation-based evaluation of the safety performance of IVSS is developed in this research and the tasks that are required to implement this methodology are discussed.
1 Introduction

A number of systems, referred to as Intelligent Vehicle Safety Systems (IVSS) or Advanced Driver Assistance Systems (ADAS), are currently under development to enhance the driving task and assist drivers in avoiding collisions. The aim of these systems is to reduce both the number of collisions and their severity and consequences by affecting several aspects of the driver-vehicle-roadway interactions. The systems in the rear-end collision avoidance group for example, aim at preventing or decreasing the severity of rear-end collisions, through the utilization of forward-looking sensor, processor and control elements. A representative example of systems in this category, although of limited capability, is the intelligent cruise control (ICC) or adaptive cruise control (ACC) that automatically maintains a predetermined time-headway between the equipped vehicle and the lead vehicle. ICC utilizes throttle modulation and down-shifting (and/or braking) to maintain this preset time-headway.

In addition to the research that is necessary to develop the required technology associated with these systems, equally important is the understanding of the safety benefits that may be realized through their introduction. A classification of twenty-four ADAS according to their impact on road safety and traffic efficiency is presented by Golias et al. [1]. The proposed classification allocates the driver assistance systems in four different categories on the basis of whether traffic efficiency and safety impact is high or low. This categorization reveals that forty percent of the systems considered are expected to have a high safety and low traffic efficiency impact, while only fifteen percent are expected to have both impacts high.

Several researchers have used simulation to study safety impacts of IVSS. The studies, in most cases, are applied to very specific situations and have used several simplified assumptions. Najm et al. [2] used computer simulations to estimate the probabilities of a crash in two rear-end pre-crash scenarios with and without the presence of Intelligent Cruise Control. Sala and Mussone [3] developed a simulation environment to assess the safety impacts of collision avoidance systems. The authors mention that an important requirement for simulators designed for safety studies, is the modeling of traffic dynamics inside platoons (clusters of vehicles traveling together), especially how drivers react to perturbations in the traffic stream. The simulator developed by Sala and Mussone models unsafe maneuvers by the deceleration of the first vehicle. Other vehicles in the platoon adapt their behavior either by applying maximum deceleration after some reaction time, or by switching to another lane. Antoniou et al. [4] developed a methodology that combines microscopic and macroscopic simulation to assess the network efficiency, environmental, and safety impacts of ADAS. The methodology is
applied to two ADAS that are most likely to be implemented, namely Adaptive Cruise Control and Intelligent Speed Adaptation. Safety impacts are obtained indirectly from the traffic efficiency results, in particular changes on average speed, headway, time-to-collision, and lane changing.

The objective of this paper is to present a comprehensive framework for simulation-based evaluation of the safety performance of IVSS. Both the expected reduction of collisions, as well as the potential reduction in their impacts are of interest. The remainder of this paper is structured as follows. The evaluation of safety benefits of IVSS is discussed in Section 2. The methodology for the simulation-based evaluation of the safety performance of IVSS is presented in Section 3. Section 4 concludes the paper with an overview of the research.

2 Evaluation of IVSS Safety Benefits

An important difference between traditional safety studies and studies in evaluating IVSS impacts is the availability of data. IVSS systems are expected to bring about significant changes in the interaction between drivers and vehicles. However, since the systems are not currently operational, data can only be collected from demonstration projects, driving simulators and traffic simulation models at an appropriate level of detail.

Methodologies for evaluation of safety benefits due to IVSS range from simple ones to very detailed. Simpler approaches use descriptive statistics of variables that play the role of safety proxies. Demonstration projects provide some of the data required (see for example Koziol et al., [5]). More detailed approaches use appropriate models to predict benefits. Important to the success of these approaches is the identification of causal variables that can explain the occurrence of collisions.

Najm and daSilva [6] have proposed the following model for the safety benefits, $B$, from IVSS: $B = N_{wo} \times SE$ where $N_{wo}$ is the number of relevant collisions without IVSS, and $SE$ (or System Effectiveness) the percent reduction in collisions due to IVSS. $SE$ can be estimated as:

$$SE = \sum_i P(S_i) \times E(S_i)$$

where:
- $i$: index indicating a particular safety-critical driving conflict that leads to a collision,
- $S_i$: a distinct safety-critical driving conflict,
- $E(S_i)$: IVSS effectiveness in mitigating collisions preceded by conflict $S_i$, and
P(S_i): ratio of relevant collisions preceded by S_i, N_{wo}(S_i), to all relevant
collisions without the assistance of IVSS:

\[ P(S_i) = \frac{N_{wo}(S_i)}{N_{wo}} \]

The values of P(S_i) can be obtained from national crash databases. The values
of E(S_i) are estimated from:

\[ E(S_i) = 1 - \frac{p_w(S_i) \times M_w(S_i)}{p_{wo}(S_i) \times M_{wo}(S_i)} \]

where:

- p_w(S_i): probability of a collision when in conflict S_i in the presence of IVSS,
- M_w(S_i): number of encounters with a safety-critical driving conflict S_i per vehicle-kilometers travel (VKMT) in the presence of IVSS,
- p_{wo}(S_i): probability of a collision when encountering a safety-critical driving conflict S_i without the assistance of an IVSS,
- M_{wo}(S_i): number of encounters with a safety-critical driving conflict S_i per VMT without the assistance of IVSS.

In order for the model to be operational, data for the calculation of M_w(S_i) is required. Najm and daSilva recommend the use of operational tests along
with simulation and other methods for the generation of the necessary information.

Godbole et. al. [7] proposed a framework for the evaluation of safety benefits from Crash Avoidance Systems (CAS). The proposed framework attempts to integrate existing approaches and results under a single umbrella, through a five level hierarchical process, called HARTCAS (Hierarchical Assessment and Requirement Tools for Crash Avoidance Systems). With the level of detail increasing from the top layer to the bottom, the five layers are:

- Benefit assessment: high-level models can be used at this level (such as the one suggested by Najm and da Silva, [6])
- System performance and user acceptance: which translates probabilistic measures related to various subsystems, such as sensing, actuation, control and human-machine interface (HMI) to the CAS system performance and user acceptance measures
- Kinematic: which models the performance of the CAS through the time-varying behavior of sensing, control, actuation and human-interface subsystems
• Dynamic: models at this level represent the vehicle/driver interactions at a rather detailed level and can be used to provide the understanding required to develop appropriate models at the kinematic level.
• Experimental: where data on driver behavior, and performance of the CAS, under various conditions, is collected and analyzed

Burgett [8] suggests general guidelines and proposes a framework for evaluating IVSS safety performance and benefits. The main elements of the proposed approach are:
• Definition of crash types
• Identification of families of situations that are representative of the crash type under consideration
• Development of initial conditions for each family
• Description of driver performance in each situation (e.g. for example reaction time) which can lead to the development of “crash prevention” boundaries
• Development of baseline conditions
• Development of IVSS conditions based on data from experiments
• Estimation of the effectiveness of the system under consideration.

Data from operational tests, current (without IVSS) conditions, and supplementary data is required for the application of this framework. Furthermore, Burgett [8] recognizes the fact that data from operational tests may contain no crashes and hence there is a need for the development of “surrogate” measures for crashes.

3 Methodology

Although traffic simulation models do not usually predict collisions directly, they can become valuable tools in studying the benefits of IVSS by
• Providing indirect measurements of interest for a wide range of conditions, and
• Generating data required by analytical safety models.

Both microscopic and nanoscopic models can be used for this purpose. Nanoscopic models provide a more detailed simulation of the situation of interest and hence, they are probably more appropriate for targeted, very specific applications. Microscopic models operate at a higher level of detail and are appropriate for more general evaluations and studies.

3.1 Evaluation framework

A framework for the evaluation of safety benefits through (microscopic) simulation is outlined in Figure 1. According to this framework, the IVSS under consideration influences the driving performance by affecting several parameters in the driving behavior models used by the simulation tool.
Examples of such parameters include the reaction time, perception of traffic conditions and situations, braking behavior, etc. As a result, the behavior of the vehicles in the traffic simulation changes in accordance to the changes in driving behavior.

Several scenarios are generated that are representative of the conditions and driving population (such as congestion levels, network geometric characteristics and IVSS penetration levels). For a given scenario, detailed output statistics are collected during the simulation. These output statistics are used to derive important safety indicators and inputs to safety models of interest. The safety indicators and the output from the safety models are used to analyze the impact of the IVSS under consideration. The analysis quantifies the evaluation and provides an understanding of the sensitivity of the impacts to various factors (such as penetration of IVSS in the vehicle fleet). Finally, the results of the analysis are also used to develop new scenarios that test the system even further.

The main components of the above framework are:
- Impact of IVSS on the driver/vehicle interactions
- Structural changes in driving behavior that may affect performance.

Figure 1. Evaluation Framework
3.2 Impact of IVSS on the driver/vehicle interactions

The impact of IVSS on the driver/vehicle interactions is an important aspect of the problem. The (in)accuracy of this information propagates through the simulation to the simulation output and ultimately determines the representativeness of the results. Data from in-depth analyses, as well as driving simulators may be used to accurately capture the impact of IVSS on the driver/vehicle interactions. A relevant application is presented by Yannis et al. [9], who combine microscopic traffic simulation and driving simulator pilot tests of vehicles equipped with Advanced Cruise Control (ACC) systems, aiming to identify traffic and safety impact of the introduction of this technology.

3.3 Structural changes in driving behavior that may affect performance

Structural changes in driving behavior due to IVSS are an important aspect to capturing IVSS impact. Hoedemaeker and Brookhuis [10], for example, studied the impact of adaptive cruise control systems on the driving behavior of four groups of drivers. The groups represented different driving styles in terms of speed and focus. The authors observed changes in the driver behavior that resulted in higher speeds, smaller minimum time headway and larger braking force. Koziol et al. [5], using results from an ICC demonstration project, report that drivers' response time was higher in the presence of ICC. However, they point out that the longer response times may be the result of ICC design aspects, as opposed to driver non-responsiveness. In any case the results suggest that all possible effects should be taken into account in order to have an unbiased benefits evaluation.

3.4 Relevant safety indicators

An important element of the evaluation framework is the definition of appropriate performance measures. Performance measures can be generated from the output data of the simulator. Critical among them are various measures, which will be used as safety indicators. Examples of safety indicators include:

- Time headway distributions
- Space headway distributions
- Acceleration/deceleration profiles and distribution across the population of drivers
• Speed profiles and distribution across the population of drivers
• Number of lane changes
• Overtaking
• Driving states and transitions
• Number of close calls

Koziol et al. [5] in their evaluation of Intelligent Cruise Control Systems, used the last two measures. Driving states describe the type of driving situation such as closing, following, separating, and cruising. Koziol et al. provide specific definition of the various states using the relative speed of the vehicles involved as determining factors. States are also divided into sub-states using the time headway and the relative speed of the vehicles as guiding factor. Sub-states for the closing state for example, include close rapidly, close moderately, etc. Transitions describe the change from one driving state to another.

Close calls are also used as a safety indicator (Koziol et al. [5]). Close calls refer to events that present near encounters with other vehicles or near run-off-road events. Koziol et al. developed a methodology for the identification of close calls and categorize them according to their severity (minor, marginal, critical, most severe) and proximity to an actual crash (near miss, hazard present, no hazard present).

Using a well-designed simulation tool the above measures can be estimated at various levels of spatial and temporal resolution. In addition, derivative measures, such as travel time and speed variability, can also be estimated.

3.5 Relevant input to safety models

In addition to the above indirect measurements the simulator should be able to provide data that can be used as inputs to appropriate safety models. For example, the application of the modeling approach suggested by Najmi and daSilva [6] requires the identification of critical conflicts. The simulation tool that will be used for benefit analysis within such a framework should be able to provide the above information.

3.6 Requirements and functionality

Based on the results of the first four components, the main requirements and functionality of the simulation tool can be established. Clearly, it is important that the output of the simulator is sensitive to the design characteristics of the IVSS under evaluation. Main required functionality includes:

• Identification of
  o Critical conflicts
  o Close calls
  o Conditions for secondary incidents
• Modeling of
3.7 Relevant scenarios
The benefits should be evaluated under various scenarios that are representative of the traffic conditions and the driver population. In order to capture an adequately wide range of the available space, scenarios should be developed along—at least—the following dimensions:

- Demand characteristics and IVSS market penetration
- Traffic congestion
- Driver characteristics
- Events (e.g. weather, incidents, etc.)

4 Conclusion
A number of systems, referred to as Intelligent Vehicle Safety Systems (IVSS) or Advanced Driver Assistance Systems (ADAS), are currently under development to enhance the driving task and assist drivers in avoiding collisions. In addition to the research that is necessary to develop the required technology associated with these systems, equally important is the understanding of the safety benefits that may be realized through their introduction.

In this research, a methodology for the simulation-based evaluation of safety performance of IVSS is presented. Relevant background is reviewed, and the overall framework is outlined. The framework components are then presented.

5 References


