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Assessing the safety effects of cooperative intelligent transport systems: A bowtie analysis approach

Ute Christine Ehlers[a,*], Eirin Olaussen Ryeng[a], Edward McCormack[b], Faisal Khan[c], Sören Ehlers[d]

[a] Department of Civil & Transport Engineering, NTNU Norwegian University of Science and Technology, 7491 Trondheim, Norway
[b] Transportation Engineering Group, Department of Civil & Environmental Engineering, University of Washington, Seattle, WA 98195-2700, USA
[c] Process Safety & Risk Engineering Group, Faculty of Engineering and Applied Science, Memorial University, St. John's, NL, A1B 3X5, Canada
[d] Institute for Ship Structural Design and Analysis, Hamburg University of Technology, 21073 Hamburg, Germany

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ABSTRACT

The safety effects of cooperative intelligent transport systems (C-ITS) are mostly unknown and associated with uncertainties, because these systems represent emerging technology. This study proposes a bowtie analysis as a conceptual framework for evaluating the safety effect of cooperative intelligent transport systems. These seek to prevent road traffic accidents or mitigate their consequences. Under the assumption of the potential occurrence of a particular single vehicle accident, three case studies demonstrate the application of the bowtie analysis approach in road traffic safety. The approach utilizes exemplary expert estimates and knowledge from literature on the probability of the occurrence of accident risk factors and of the success of safety measures. Fuzzy set theory is applied to handle uncertainty in expert knowledge. Based on this approach, a useful tool is developed to estimate the effects of safety-related cooperative intelligent transport systems in terms of the expected change in accident occurrence and consequence probability.

1. Introduction

The transport policy of most countries seeks to improve road traffic safety by reducing the number of road fatalities and severe casualties (e.g. WHO, 2004; Swedish Road Administration, 2006; OECD/ITF, 2008; EC, 2011). A generally applicable approach contributing to this target are *intelligent transport systems* (ITS) applying advanced *information and communication technologies* (e.g. OECD, 2003; EC, 2006). The number of people killed or injured in road traffic accidents depends primarily on the factors *exposure, accident rate* and *injury severity*; see Eq. (1) (Nilsson, 2004; Elvik, 2009):

$$Number\ of\ injured = Exposure \times \left(\overset{\text{Risk}}{\frac{Number\ of\ accidents}{Exposure}}\right) \times \left(\overset{\text{Consequence}}{\frac{Number\ of\ injured}{Number\ of\ accidents}}\right)\ Number\ of\ fatalities = Exposure \times \left(\frac{Number\ of\ injured}{Exposure}\right) \times \left(\frac{Number\ of\ fatalities}{Number\ of\ injured}\right) \quad (1)$$

Exposure to the risk of a road accident is usually referred to as the amount of travel, i.e. the number of person or vehicle kilometers. *Accident rate* is the risk of a road accident per unit of exposure, and serves as an indicator for the probability of accident occurrence. The higher the accident rate, the higher the probability of an accident on a given trip of a given length. The term *accident risk* is often used simultaneously with accident rate. *Injury severity* refers to the outcome or consequence of accidents in terms of fatally or otherwise injured people. In principle, each of the three factors listed above, exposure, accident rate and injury severity, can directly or indirectly be influenced by ITS (e.g. ETSC, 1999; Kulmala, 2010). Some ITS can decrease the amount of travel and influence traffic participants to choose a traffic mode that is associated with a lower accident risk. Examples include route guidance systems, road pricing schemes or systems giving priority to public transport. Other ITS applications, such as lane departure warning-, intelligent speed

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* Corresponding author.
E-mail addresses: ute.ehlers@ntnu.no (U.C. Ehlers), eirin.ryeng@ntnu.no (E.O. Ryeng), edm@uw.edu (E. McCormack), fikhan@mun.ca (F. Khan), ehlers@tuhh.de (S. Ehlers).

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adaptation- and emergency call systems, are supposed to directly reduce the risk and severity of accidents. The focus of this study is on the latter type of systems, hereafter called 'safety-related ITS'. The traffic safety concept mentioned above shall not be confused with the traditional definition of $risk = probability * consequence$ that combines the probability of occurrence and the consequence of one specific hazardous event. However, the latter concept will be used later on in the bowtie analysis part.

The OECD (2003) classifies ITS technologies into three main groups: vehicle-based systems, infrastructure-based systems, and cooperative systems. *Vehicle-based* or *in-vehicle systems* are applied within the car and their purpose is to support or to improve the driver's decision-making and performance. *Infrastructure-based systems* or *roadway ITS* are applied at the roadside and are often meant to regulate the driven speed in order to improve traffic flow and/or road traffic safety. For the latter, the drivers are informed or warned in a timely manner about unexpected incidents or hazards ahead, with the expectation that they adapt their driving to this warning, thus avoiding a collision. *Cooperative ITS* (C-ITS) utilize both vehicle- and infrastructure-based systems with temporary communication links between them. Information and communication technologies are placed at the roadside and inside vehicles to collect, transfer, process and deploy traffic- and safety-related data. By means of wireless short range radio communication between the road infrastructure and vehicles (and indirectly also the driver), cooperative ITS are created, and road safety is expected to be improved by decreasing the number of accidents and severe casualties. The following wireless communication interactions can be utilized: (a) *vehicle-to-vehicle communication (V2V)* and (b) *vehicle-to-infrastructure (V2I)* or *infrastructure-to-vehicle communication (I2V)*. The communication between the C-ITS components can be *one-way* or *two-way* (OECD, 2003). For further details on C-ITS, see for example Bayly et al. (2007) or Harding et al. (2014).

Examples of (potential) safety-related applications in a cooperative environment are in-vehicle signage (I2V, V2V), intelligent speed adaptation (I2V), cooperative adaptive cruise control (V2V), lane change assistants (V2V), emergency call systems (V2I), and various incident detection and warning systems like local danger warning (V2V, I2V), traffic jam ahead warning (V2V, I2V) or approaching emergency vehicle warning (V2V).

The debut of cooperative ITS dates back about two decades and started in Europe with the programs PROMETHEUS (PROgraM for European Traffic with Highest Efficiency and Unprecedented Safety) (Williams, 1988) and DRIVE (Dedicated Road Infrastructure for Vehicle safety in Europe) (DRIVE, 1989). Similar initiatives and programs were launched in the United States (IVHS America, 1992) and Japan (Nakamura et al., 1994) around the same time. To date, C-ITS are highly advanced ITS equipped with automated information and communication technologies – but, they barely exist yet and are at best in their test phase with the exception of emergency call systems and some intelligent speed adaptation applications (e.g. Wilmink et al., 2008; Vaa et al., 2014). They are an emerging technology and mainly innovations of the near future that slowly but surely materialize. Navigation- and telecommunication devices already transmit and receive positioning data, and vehicles and road infrastructures are able to detect relevant data through sensors, radars and cameras. In principle, everything that can be perceived and detected can also be communicated. That means it is only a question of time that the necessary steps from ITS to cooperative ITS are taken and that prompt communication between vehicles and the roadway becomes reality. This communication link is one of the missing parts in order to do the next step towards fully automated driver assistance.

Since the late nineties, it has been of major interest to assess the effects of ITS on mobility, ecology, traffic flow and road safety. The current amount of literature is extensive, due to the large number of systems and their development. However, there are only few systematic reviews that focus on ITS and their actual safety effects, meaning their effect on accidents. This shows that even the safety effect of existing, non-cooperative ITS cannot be reliably estimated on the basis of accident studies yet, because their statistical basis is limited. Literature reviews on ITS in general and their expected and observed effects on road safety and driver behavior were performed by ETSC (1999), Bayly et al. (2007), Linder et al. (2007), Spyropoulou et al. (2008), Patten (2013) and Martens (2013). Systematic state-of-the-art analyses with focus on the effects of ITS on accidents were made by Vaa et al. (2007) and Elvik et al. (2009). Wilmink et al. (2008) and Vaa et al. (2014) performed ex-ante estimate studies on the safety effects of ITS; and Schirokoff et al. (2012) and Harding et al. (2014) on the safety effects of C-ITS. Ex-ante estimate studies are based on in-depth investigations of accidents. They are used to analyze whether accidents or fatalities could have possibly been prevented if a particular safety measure would have been used. Nevertheless, research on the safety effects of C-ITS specifically is almost nonexistent, because the majority of such systems is still under development or in prototype phases or, at best, has only entered the market to a limited extent. In addition, there is an even bigger challenge when assessing the safety effects of C-ITS. As these systems are cooperative, a substantial portion of the vehicles on the road needs to be equipped with C-ITS, before the anticipated safety effect would occur. It may take years, if not decades, before this scenario becomes reality.

To note some road safety effect evaluation studies of (C-)ITS, Vaa et al. (2014) estimated the maximum potential safety effects of *Intelligent Speed Adaptation* (ISA) and *Adaptive Cruise Control* (ACC), amongst other driver support systems, using Norwegian accident data. An in-depth accident study in Finland (Virtanen et al., 2006) estimated the potential safety effect of *eCall* – the emergency call system that has been developed for and by the European Union (EC, 2015). Elvik et al. (2009) estimated the effects of various *variable message signs* (VMS) based on meta-analyses. Wilmink et al. (2008) performed an ex-ante estimate study on the safety effects of a *local danger warning system*, amongst others. Harding et al. (2014) performed a complex ex-ante estimate study using accident data/statistics and manifold computer simulations to assess the safety effectiveness and benefits of two cooperative systems: *intersection movement assistant (V2V)* and *left turn assistant (V2V)*. Schirokoff et al. (2012) estimated the safety effect of a *cooperative intersection safety system (V2V, I2V)*, including right-turning-, left-turning-, crossing-, traffic-light- as well as stop-line assistance, with an ex-ante estimate study. Each study concluded on significant improvements in road traffic safety, in terms of a significant reduction in the number of accidents, injuries and/or fatalities. These safety effects of (C-)ITS were assessed using a *variety of methods*, which can be classified as follows. Vaa et al. (2007), and similarly the ETSC (1999), distinguish between (a) *accident study methods* and (b) *"by proxy" or surrogate methods*, see Table 1.

Accident study methods have been used to measure the actual safety effects of mature ITS, like electronic stability control (ESC) and anti-lock brake systems (ABS), that have been implemented under real traffic conditions long enough in order to collect significant amounts of accident data. Thus, accident study methods are suitable for assessing long term effects of ITS. However, long periods of traffic exposure are necessary to collect a significant level of accident data. This situation is difficult to reach when it comes to safety-related (C-)ITS that are relatively new or are only used in small scale. *"By proxy" or surrogate methods* have been used to assess the safety effects of relatively new ITS that are not yet implemented in real traffic, or have been implemented for a relatively short time – which is the case for the majority of ITS. This indicates that surrogate methods are suitable for evaluating short term effects, which may, however, substantially differ from the long