SAFETY AND OPERATIONAL BENEFITS OF LIMITING THE DRIVING FREEDOM OF HIGH-RISK DRIVERS AND ASSISTING NORMAL DRIVERS

Filmon G. Habtemichael [a*] *(filmon.habtemichael@ist.utl.pt * corresponding author)*

Luis de Picado Santos [a] *(picado.santos@civil.ist.utl.pt)*

[a]*CESUR – DECivil – Instituto Superior Tecnico (IST), Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon-Portugal*

ABSTRACT

The causation factor for the majority of road traffic crashes is presumed to be driver error. Besides blaming drivers none or little is done to assist them so that they would be better performers. This research aims at reducing the driving task demand of drivers. Drivers are segmented into two groups: High-Risk Drivers and Normal Drivers. High-risk drivers are group of drivers whose rate of crash involvement is believed to be more than normal drivers. This research proposes limiting the driving degree of freedom of high-risk drivers so that their following headway, cruising speed and freedom of changing lanes are restricted. For normal drivers, implementation of variable speed limit (VSL) is proposed to homogenize their driving behavior and the impact of the level of compliance of drivers to VSL is examined. VISSIM microsimulation program and Surrogate Safety Assessment Model (SSAM) are used to evaluate the safety and operational benefits of limiting the driving degree of freedom of high-risk drivers of proportions of 4%, 8% and 12% of total drivers as well as assisting the rest of normal drivers using VSL. Reduction in simulated vehicle conflicts and travel time are used as indicator for safety and operational benefits respectively. The results suggest that limiting the freedom of high-risk drivers has a potential to reduce the occurrence of simulated vehicle conflicts by as much as 68% and savings of 1% in travel time depending on the level of traffic congestion. Similarly, assisting normal drivers using VSL resulted into reduction of 75% of simulated vehicle conflicts and saving of 16% in travel time depending on the level of traffic congestion. The research concludes that safety and efficiency challenges of the road transportation system can be considerably ameliorated by limiting the driving degree of freedom of high-risk drivers and assisting normal drivers.

Key words: Traffic safety, Traffic management; Traffic simulation; SSAM; VISSIM; High-risk driving; VSL

1. INTRODUCTION

Over the past years, advances in vehicle technology, infrastructure engineering and traffic management have contributed in decreasing roadside crashes and fatalities. The reward from these advances was a steady decrease in the number of fatalities until late 90s. However, over the past 10 to 15 years, the number of fatalities in the developed countries has kept more or less a constant trend with very slight reduction (WHO, 2004). This suggests that the aforementioned advancements might have reached their capable limit of decreasing crashes and fatalities. As a result, road safety research has been focused towards minimizing the occurrences and mitigating the consequences of driver errors and assisting drivers to be better performers in the road transport system.

Studies by Stanton and Salmon (2009a; 2009b) and Sun et al. (2008) mentioned that about 75 to 95% of crashes are related to one or more driver errors. Archer and Kosonen (2000) observed that drivers do make one driving error every two minutes or every 2km of driving distance while travelling at 60km/h. Harvey et al. (1975) defined driver error as '… any action or lack of action by driver that would require them to implement a correction in order to make the situation safe again'. According to Reason (1990) human errors are classified into slips, mistake and violations. Slips and mistakes refer to attentional and memory failures while violations are willful and deliberate actions that compromise safety. Hutabarat et al. (2004) mentioned that driver errors could be due to inadequate experience and skills (slips and mistakes) or willful inappropriate actions (violations). However, the majority of the driving errors by high-risk drivers were intentional violations rather than errors of slips and mistakes which suggest that such behavior does not immediately result from lack of driving skill but from inappropriate driving behavior (Rolls and Ingham, 1992). The most common high-risk driving errors include: speeding, close following, abrupt lane-changing and impaired driving. Other high-risk driving errors include internal and external distractions, carelessness and recklessness, violating traffic signs, aggressive driving and the like.

In this research work, drivers are categorized into two divisions, namely: High-risk drivers and Normal drivers. High-risk drivers are a subset of drivers whose involvement in crashes is found to be higher relative to normal drivers. They are continuously engaged in activities that would increase their driving task demand or increase their exposure to crashes which ultimately endangers the safety of their own and other road users. High-risk drivers constitute only small segment of the total drivers; however, they disproportionately represent the majority of the road traffic crashes. For example, Guo and Fang (2012) found that high-risk drivers make up only 6% of the driving population but accounted for 65% of total crashes and near crashes.

This paper suggests limiting the driving degree of freedom of high-risk drivers to counteract the common driving errors they usually demonstrate. This is to say that the driving degree of freedom of high-risk drivers is restricted by means of limiting the maximum speed they can driver at, the freedom of changing lanes and the minimum following distance they can keep. In other words, driver competence and level of performance is used as an additional traffic management criterion to reduce the common high-risk driving errors and decrease their driving task demand. On the other hand, variable speed limit (VSL) is proposed as a means to assist normal drivers so that their driving task demand is reduced and are supported to be even safer driver. In doing so, the importance of driver compliance to VSL is explored and its benefits on safety and operations of motorway traffic are examined. VSL, by definition, is an ITS measure for traffic management in which the speed limit of motorway sections change in response to real-time traffic, road and weather conditions with an attempt to harmonize the traffic flow and improve safety by reducing speed variation among vehicles across lanes, within the same lane and also between upstream and downstream traffic flows. This in turn reduces the frequency of lane-changing maneuvers and crash potential situations. To estimate the safety and efficiency benefits of such traffic management strategy, VISSIM microscopic traffic simulation and Surrogate Safety Assessment Model (SSAM) are employed in this research work.

The structure of this paper is as follows. After a general overview of the theme idea of the research work, review of literature on the task of driving, typology of drivers and the impact of high-risk driving are presented. Afterwards, the credibility of the adopted methodology of the research is discussed. Finally, conclusions and future works are presented following the discussion of results on safety and operational benefits of traffic from limiting the driving degree of freedom of high-risk drivers and assisting normal drivers.

2. LITERATURE REVIEW

The task of driving

Fuller (2000, 2005) developed the Task-Capability Interface model which describes the task of driving. The model formulates the concept of driving task difficulty as the determinant factor for crash involvement. Driving task difficulty is the outcome of the dynamic interface between the demand of the driving task and the available capability of the driver, i.e. the task of driving can be easy or difficult depending on the demand of the driving task and the driver’s reserve of capability to control the vehicle.

According to Fuller (2005) and Fuller and Santos (2002), the driving task demand is dictated by driver’s choice of speed, headway, magnitude of gap accepted, nature of traffic, behavior of other road users and environmental factors of driving such as visibility and road alignment. In the same way, the capability of driver is limited by acquired characteristics and biological factors which include knowledge of road rules, driving skills, training and experience, human limitations in information processing, reaction time as well as physical strength and flexibility. Combining the concepts of driver capability and the driving task demand gives rise to the Task-Capability Interface model which states that: ‘If capability exceeds the driving task demand, then the driver is able to progress safely. However if capability falls short of task demand, then collision or loss of control is implied’ (Fuller and Santos, 2002, page 6). Furthermore, since driving is a self-paced task, drivers can adjust their driving task demand by modifying their speed, following headway, making strategic selection of route to destination or adjusting timing of journey to avoid congested roads or rush-hours that increase their driving task demand (Fuller, 2005).

According to Hutabarat et al. (2004), the task of driving involves a complex interaction between human factors and system response with the sequence of problem recognition, decision making and execution of a maneuver, though it could be difficult to pinpoint the boundaries. An error in one or more of these steps results into situation of a crash or near crash. Problem recognition errors involve failure to yield a stop sign, delay in problem recognition, inattention and distractions. Decision errors are like excessive speed, improper maneuver, tailgating, misjudgment of distance or closure and excessive acceleration. Execution errors include evasive actions, inadequate directional control, panic or freezing.

Risk taking behavior of drivers

Not all drivers are equally safe nor do they possess a homogenous behavior and perception towards risky driving. The important aspect of driver safety is the ability of the driver to keep a suitable margin of safety by constantly examining his or her driving capability and the driving task demand. Fuller (2005, 2008) called this 'calibration' of drivers and it allows them to precisely estimate the driving task difficulty. Safer drivers are well calibrated and supposedly have wider margin of safety. One method of assisting drivers to maintain their task difficulty within a safe margin is by prescribing an optimal speed in response to the real-time traffic conditions. On the other hand, since high-risk drivers are poorly calibrated in terms of underestimating the driving task demand and/or overestimating their capability, they have little or no safety margin. Thus, high-risk drivers unnecessarily increase their driving task demand by speeding, following closely, changing lanes abruptly or choosing to drive while their driving capability is very low, e.g. impaired driving due to sleep or intoxicated.

In the same way, Evans (1991, 2004) distinguished between driver performance and driver behavior. Driver performance is what a driver CAN do (his/her driving skill) while driver behavior is what a driver actually DOES (his/her driving style). In other words, driver performance refers to the driver's knowledge, capability, perceptual and cognitive abilities in controlling the longitudinal and transverse trajectories of his/her vehicle. On the other hand, driver behavior refers to the reason why a driver chooses to perform certain high-risk actions. Evans suggested that a good driving performance can be overruled by a risky behavior.

Risk taking behavior of drivers increases the probability of involvement in crashes. Evans (1991) defined risky driving as any behavior that increases the driving task difficulty and compromises the road safety. Similarly, Boyce (1999) outlined risk taking behavior as any action that '… increases driving task difficulty by: a) decreasing the reaction time necessary for successful evasive maneuvering, b) diverting attention away from the driving task, or c) increasing response time to perform typical driving behaviors.' (page 13-14). Regardless of the driving situation, some drivers are habitually active in risky driving and can be labeled as high-risk drivers (see Musselwhite, 2006; Fuller et al., 2008; Guo and Fang, 2012).

Typology of drivers

An attempt to categorize drivers based on their attitude and perception towards risky driving is the first step in planning or designing interventions to improve their safety. Thus, a number of research works based on questionnaire survey and self-reports as well as naturalistic driving studies have been aimed at investigating the risk taking behavior of drivers and accordingly tried to formulate a typology of drivers in relation to risky behavior. To mention some, Fuller (2007) and Fuller et al. (2008) identified four different types of drivers; namely, high-risk threshold, low-risk threshold, opportunistic and reactive risk takers. In regard to motivation of drivers towards risk, Musselwhite (2006) categorized drivers into four groups: unintentional risk takers, reactive risk takers, calculated risk takers and continuous risk takers. Similarly, Harré (2000) categorized drivers based on their driving behavior as: habitual cautious driving, active risk avoidance, reduced risk perception, acceptance of risk as a cost and risk seeking. Similarly, Broughton and Stradling (2005) classified motorcycle riders into: risk aversive, risk acceptors and risk seekers. A naturalistic driving study by Guo and Fang (2012) developed three types of drivers: low-risk, moderate-risk and high-risk drivers.

Based on the above mentioned literature, drivers can be broadly categorized into two divisions: High-Risk and Normal Drivers. The literature suggests that high-risk drivers make up anywhere from 6% to as much as 14% of the driving population. High-risk drivers are well identified in terms of their psychological and demographic characteristics. They include the family of drivers who are young, inexperienced and recidivists with higher crash rates than others. The psychological makeup of these individuals in terms of the five-factor NEO inventory is low relative to safe drivers. High-risk drivers enjoy speeding (driving above the speed limit or too fast for the prevailing conditions), following closely (tailgating), overtaking dangerously and are frequently distracted (for example, see Musselwhite, 2006; Guo and Fang, 2012).

3. METHODOLOGY

A 7km stretch of BRISA motorway (A-5) around Lisbon, Portugal, with a 2% heavy goods vehicles and several on-off ramp facilities was modeled, calibrated and validated in VISSIM microscopic traffic simulation program. The simulation was carried out using various vehicle classes which represent normal and high-risk drivers who speed, follow closely, change lanes abruptly and drive while impaired. Though simulations representing all traffic conditions was conducted and safety as well as efficiency benefits of motorway traffic from limiting the driving degree of freedom of high-risk drivers and assisting normal drivers is estimated, particular attention is given to relatively congested traffic conditions. This is due to the fact that high-risk driving errors are most commonly practiced (Sarkar et al., 2000; Horne and Reyner, 1999) and assisting drivers is vital during rush hours. To reflect the stochastic nature of motorway traffic, 10 simulation runs of each model were conducted by changing the random seeds of the simulations in VISSIM. All simulations were carried out at the finest simulation resolution of 10 simulation steps per second.

Calibration and validation of base model

VISSIM provides a set of adjustable parameters that determine the behavior of the simulated vehicles. In the first place, the base model was calibrated by fine tuning VISSIM's driver behavior parameters and traffic volume inputs so that it represents the real and day-to-day operations of the simulated motorway stretch (Chitturi and Benekohal, 2008; Menneni et al., 2008). Average speeds and vehicle counts from the simulation output and real world measurements from loop detectors placed at three locations on the motorway were used for calibration and validation purposes. To enhance the precision of the calibration process, the averages of speed and traffic count were contrasted at aggregation intervals of 5 minutes. Geoffrey E. Heavers (GEH) statistic which is a modified chi-square statistics, commonly applied for traffic engineering purposes, has been employed to compare the fitness between the simulated and observed traffic variables of speed and vehicle count (see equation 1).

$$\boldsymbol{GEH = [(simulated - observed)^2 / 0.5 * (simulated + observed)]^{0.5}} \qquad (1)$$

The advantage of GEH is that it comprises both the relative and absolute differences between the simulated and observed data sets (Holm et al., 2007). The calibrated model had an overall GEH value of 1.83 and was validated against observed data sets independent of the calibration data and provided an overall GEH value of 1.92. By convention, a GEH value less than 5 is considered to be a good fit, GEH value between 5 and 10 requires further investigation, while GEH value above 10 is a bad fit (Holm et al., 2007).

Simulation-based safety analysis and surrogate measures

Safety evaluations of a traffic stream have been a challenging task for traffic engineers and several traditional models have been developed to address the issue. According to Gettman and Head (2003), majority of these models work based on historic crash information which requires years of crash data for statistical significance. In other words, engineers have to wait for crashes to happen, putting human live on the line, in order to evaluate the safety of a facility. This makes the traditional models practically useless to estimate the safety performance of a traffic management strategy which is not yet deployed. The cost, accuracy and transferability of these models are also of great concern (see Ozbay et al., 2008; Gettman and Head, 2003; Gettman et al., 2008).

To overcome the aforementioned shortcomings of the traditional safety evaluation models, several authors proposed the use of microscopic traffic simulation and analysis of simulated vehicle conflicts as surrogate measure for safety (Ozbay et al., 2008; Archer and Kosonen, 2000; Minderhoud and Bovy, 2001; Gettman et al., 2008). The notion of these authors is that simulated vehicle conflicts are correlated to actual crashes in a certain way. Microscopic traffic simulation-based safety analysis provides a fast and cost-effective means of evaluating safety of traffic. Recently, the technique of simulated vehicle conflicts has been commonly employed for analyzing safety of a simulated traffic stream. The speed and acceleration of the simulated vehicles, both in time and space, can be obtained from the output of simulation platforms and the trajectories of vehicles can easily be used to determine possible conflicts among them (Ozbay et al., 2008; Gettman and Head, 2003).

Surrogate Safety Assessment Model (SSAM) is a package developed by FHWA for safety evaluation of simulation models using the technique of vehicle conflicts. Safety assessment in SSAM is done by analysis of possible conflicts between vehicles along their trajectories. Depending on the angle of conflict, the detected conflicts are further classified into rear-end, lane-changing and crossing conflicts. It has to be noted that SSAM represents only conflicts between two vehicles. Multi-vehicle crashes and single-vehicle crashes like rolling-over, collision with motorway side rails and running off the roadway can’t be captured with the technique of vehicle conflict. SSAM provides a number of surrogate safety measures for every detected conflict that can be used to determine the probability of a conflict to be an actual crash and the severity level of the resulting crash (Gettman and Head, 2003; Gettman et al., 2008).

The number and nature of the simulated vehicle conflicts are used as surrogates for safety. Nezamuddin et al. (2011) and Habtemichael and Picado-Santos (2012a, 2012b, 2013a, 2013b) have used SSAM to evaluate safety of a proposed motorway traffic management strategies.

Hypothetical and low-speed crashes of Time-To-Collision (TTC) = 0 are filtered out from the analysis of simulated vehicle conflicts. The former is because of the vehicle overlaps at vehicle-generation points in the simulation platform and the later is because low-speed crashes are not likely to happen on motorways which are meant to provide high speed mobility. Student's t-test analysis of before-after (95% confidence interval) is conducted to determine the statistical significance of the change in safety and efficiency on motorway traffic from limiting the driving degree of freedom of high-risk drivers.

Validating SSAM: correlating simulated vehicle conflicts with historic crashes

According to Tarko et al. (2009) for a crash surrogate to be meaningful, it should fulfill two conditions:

- **i.** It should be based on an observable non-crash event that is physically related to crashes in a predictable and reliable way, and
- **ii.** There should be a practical method for converting the non-crash events into a corresponding crash frequency and/or severity.

To validate the use of SSAM and check the robustness of the model calibrated from traffic variables (speed and flow), an attempt was done to correlate the count of simulated vehicle conflicts with frequency of real crashes. A five year historic crash record (2005-2009) for the simulated motorway stretch was obtained from the Portugal National Authority for Road Safety. Since safety assessment using SSAM focuses on conflicts between two vehicles, the historic crash data was sorted by removing all instances of single-vehicle crashes like run-off crashes. As a result, the number of crashes was reduced to 293 two-vehicle crashes from a total of 447.

For correlating simulated vehicle conflicts with real crashes, 12 simulations each representing two hours of traffic were conducted to represent traffic operations of a typical weekday (24 hours). Similarly, the historic crash record was also sorted in intervals of two hours in conformity with the simulated traffic, and thus making a total of 12 dataset pairs. This was done to represent the variations in volume of traffic and frequency of crashes during the hours of a day. After running the 12 simulations, the vehicle-trajectories were analyzed using SSAM and the counts of simulated vehicle conflicts were obtained. These conflicts were correlated to historic crashes as shown Figure 1. Log-Quadratic equation was used to fit a curve (see Equations 2 to 4). Using statistical software R, the goodness of the fitted curve was assess (R^2 = 0.923) and model parameters α, θ and β were estimated to be 0.147, -0.841 and -0.216 respectively.

$$Ln(Crashes/hour/Year) = \alpha(ln(Conflicts/hour))^2 + \theta(ln(Conflicts/hour)) + \beta \qquad (2)$$

$$Crashes/hour/Year = e^{[\alpha(\ln(Conflicts/hour))^2 + \theta(\ln(Conflicts/hour)) + \beta\,]} \qquad (3)$$

$$\boldsymbol{Expected\ Crashes/hour/Year = e^{[0.147(ln(Conflicts/hour))^2 - 0.841(ln(Conflicts/hour)) - 0.216]}} \qquad (4)$$

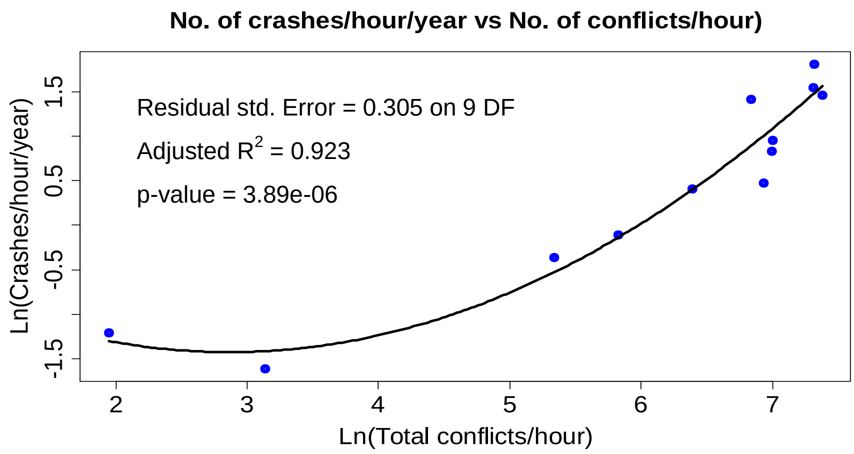

FIGURE 1 - Correlating simulated vehicle conflicts with historic crashes

4. RESULTS AND DISCUSSIONS

Given the assumption that drivers are classified in two categories, high-risk drivers and normal drivers, the results of this research work are presented separately for both sub-categories of drivers. In other words, the safety and operational benefits of limiting the driving degree of freedom of high-risk drivers as well as assisting normal drivers using VSL are presented in this section.

4.1. High-Risk Drivers: Limiting their driving degree of freedom

In this work, detection and correction of high-risk driver errors using state-of-the-art ITS devices is presumed. Accordingly, limiting the driving degree of freedom of high-risk drivers is implemented in several ways in response to the repeated errors they makes. This includes mandatory use of ITS devices that decrease the driving task demand of high-risk drivers. For speeding drivers, their speed is limited using either speed limiters or speed control systems so that drivers would not drive too fast for conditions or over the legal speed limit. For close following drivers, their following time headway (distance) is continuously monitored and maintained not to be less than a safe value using adaptive cruise control. Management of drivers who change lanes abruptly is performed by restricting their lane-changing freedom (except for necessary lane-changing maneuvers that allows them to make it to the entry and exit ramps). Finally, impaired drivers are forced to stop driving since "… the energetic state of the *[impaired]* drivers is inappropriate or insufficient to sustain a safe and accurate level of vehicular control" (Brookhuis et al., 2003) and thus should removed from the motorway traffic.

Modeling High-risk Drivers

Modeling high-risk drivers was done by changing the values of the most decisive parameters that reflect the commonly practiced errors while the rest of the parameters are left unaltered from the calibrated values. Table 3 provides the comparison of VISSIM's driver behavior parameters for normal and high-risk drivers (see Habtemichael and Picado-Santos, 2012a and 2012b). For comprehensive understanding of the VISSIM's driver behavior parameters, their sensitivity analysis and ways of calibrating a simulation model in VISSIM see (Park and

Schneeberger, 2003; Lownes and Machemehl, 2006a; b; Holm, et al., 2007; Habtemichael and Picado-Santos, 2013a; PTV, 2009).

In this research work, the works of Lownes and Machemehl (2006a) as well as Habtemichael and Picado-Santos (2012a, 2012b, 2013a) has been used as a guide for simulating high-risk drivers. Modeling of drivers who speed up was conducted by modifying the parameters that are related to speed and acceleration in the car-following model of VISSIM. For example, AAA (2009) stated that high-risk drivers exceeded speed limit by at least 25km/h and thus the 'desired speed distribution' of the vehicles that represent speeding drivers was set to be 120-150km/h. Similarly, tailgating drivers were found to follow a vehicle at a distance of as short as 15m while cruising at 80km/h (Harder et al., 2008). Thus the 'headway time' for vehicles representing the drivers who follow closely was modified to be 0.5sec. The 100-Car Naturalistic Driving study revealed that driver's lack of attention lasted a minimum of 2 seconds (Klauer et al., 2006) and thus 'temporary lack of attention' was set accordingly. Table 1 provides summary of calibrated driver behavior parameters for normal drivers and modified parameters for high-risk drivers (Habtemichael and Santos, 2012a, 2012b).

TABLE 1 - Calibrated and modified values of modeling normal and high-risk drivers.

High-risk driving Error	VISSIM driver behaviour parameters	Modified value (high-risk drivers)	Calibrated value (normal drivers)
Close following	Headway Time (CC1)	0.50 sec	0.90 sec
	Threshold for 'Following' (CC3)	-4.00	-8.00
Speeding	Desired Speed Distribution	Min. 120 & max. 150km/h	Min. 70 & max. 120km/h
	Acc. at 80 km/h (CC9)	2.29 m/s^2	1.50 m/sec^2
Abrupt lane-changing	Max. look back distance	25.00m	150.00m
	Safety distance reduction factor	0.30	0.60
Impaired driving	Max. look ahead distance	30.0m	250.0m
	Max. look back distance	10.0m	150.0m
	Duration of luck of attention	2.0sec	-

Safety benefits of limiting the driving freedom of high-risk drivers

Following the literature on driver typologies and their compositions, several proportions of high-risk drivers are considered in this research work; namely, 4%, 8% and 12% where high-risk driving errors of speeding, close following, abrupt lane-changing and impaired driving are represented equally (i.e. each high-risk driving error make-up 1%, 2% and 3%). Table 2 shows reduction of simulated vehicle conflicts from limiting the driving degree of freedom of high-risk drivers that corresponds to different proportions of high-risk drivers during relatively congested traffic conditions (Level of Service of D). It can be shown that limiting the driving degree of freedom of high-risk drivers have significantly decreased the count of total simulated vehicle conflicts by 28%, 60% and 90% for the proportions of high-risk drivers of 4%, 8% and 12% respectively. All the reductions in simulated vehicle conflicts were found to be statistically significant. Using the equations (4), it can be implied that the percentage reductions in the simulated vehicle conflicts amounted into reduction of expected crashes by 21%, 46% and 68% for the proportions of high-risk drivers of 4%, 8% and 12% respectively.

TABLE 2 - Comparison of simulated vehicle conflicts at different proportions of high-risk drivers and after limiting their driving degree of freedom (all with replications = 10, DF = 18, alpha = 0.05 and t-critical = 1.734)

Proportion of high-risk drivers	Conflict Types	Mean (Base-model)	Mean (limiting driving freedom)	t value	p value	Significant	Mean Reduction	Percentage Reduction
4% high-risk drivers (1% each high-risk driving error)	Rear-end	44.9	36.9	2.633	8.44E-03	**YES**	-8.0	**-22%**
	Lane-changing	18.0	12.4	4.715	8.63E-05	**YES**	-5.6	**-45%**
	Total	**62.9**	**49.3**	**4.53**	**1.30E-04**	**YES**	**-13.6**	**-28%**
8% high-risk drivers (2% each high-risk driving error)	Rear-end	60.8	36.9	8.348	7.0E-08	**YES**	-23.9	**-65%**
	Lane-changing	18.2	12.4	3.891	5.35E-04	**YES**	-5.8	**-47%**
	Total	**79.0**	**49.3**	**11.489**	**<1.0E-08**	**YES**	**-29.7**	**-60%**
12% high-risk drivers (3% each high-risk driving error)	Rear-end	70.5	36.9	11.648	<1.0E-08	**YES**	-33.6	**-91%**
	Lane-changing	23.3	12.4	5.695	1.06E-05	**YES**	-10.9	**-88%**
	Total	**93.8**	**49.3**	**13.459**	**<1.0E-08**	**YES**	**-44.5**	**-90%**

The safety benefit of limiting the driving degree of freedom of high-risk drivers was also investigated at lightly congested (Level of Service of C) and non-congested (Level of Service of B) traffic conditions. During lightly congested traffic conditions, the reductions in simulated vehicle conflicts for high-risk driver proportions of 4%, 8% and 12% were found to be 17%, 54% and 57% respectively. These reductions in simulated vehicle conflicts amounted to 8%, 16% and 26% reduction in expected crashes on the facility. Similarly, the reductions in vehicle conflicts from limiting the driving degree of freedom of high-risk drivers of proportions 4%, 8% and 12% during non-congested traffic conditions was found to be 24%, 70% and 97% respectively. These reductions in the count of simulated vehicle conflict during non-congested traffic conditions amounts to 4%, 12% and 17% reduction in expected crashes of the facility.

Operational benefits of limiting the freedom of high-risk drivers

Limiting the driving degree of freedom of high-risk drivers also showed some benefits on operations of motorway traffic and particularly reduction in travel time. During congested conditions, there were savings in travel time of nearly 1% for every proportion of high-risk drivers considered. Similar savings in travel time were also demonstrated in lightly congested and non-congested traffic conditions for all proportions of high-risk drivers considered (about 1% reduction in travel time). Given the fact that operations and safety of traffic are interdependent on each other, another means of improving the operations of motorway traffic is by improving the safety of the motorway traffic. Safer roads are operationally more efficient that unsafe roads. Therefore, limiting the freedom of high-risk drivers will certainly improve motorway traffic operations in terms of homogenizing the behavior of drivers which is an important factor for harmonizing the traffic flow and illuminating or reducing nonrecurring congestions due to accidents and incidents on the motorway traffic. As shown previously, the reductions in the expected crashes could be regarded as major positive achievement in operations of motorway traffic. This shows that limiting the driving degree of freedom of high-risk drivers is beneficial from both points of views of safety and operations of motorway traffic.

4.2. Normal Drivers: assisting drivers using VSL

Defining driver compliance levels

This paper also investigates the safety and operational benefits of assisting drivers using VSL. In doing so, the importance of driver compliance levels is investigated and the magnitude of the safety and efficiency benefits of VSL are quantified. Four different compliance levels are considered and they are:

- **i.** Low compliance – only 25% of drivers comply to VSL
- **ii.** Medium compliance – only 50% of drivers comply to VSL
- **iii.** High compliance – only 75% of drivers comply to VSL
- **iv.** Very high compliance – 100% of drivers comply to VSL

Modeling driver compliance to VSL

Two vehicle classes were used to represent compliant and non-compliant vehicles. Therefore, the desired level of driver compliance to VSL was achieved by varying the proportions of the vehicles representing the compliant and non-compliant drivers within the motorway traffic. Driver compliance was modeled by using the features of ‘desired speed distribution’ and ‘desired speed decision point’ which are basic input parameters of VISSIM (see Fudala and Fontaine, 2010; Park and Yadlapati, 2003; PTV, 2009). In doing so, a speed-volume VSL algorithm was applied. The algorithm is composed of five different speeds for various threshold of traffic volume (i.e. 120, 100, 80 and 60km/h corresponding to hourly traffic volume of 1200, 1500, 1800 and 2000veh/h/lane). The parameter ‘desired speed decision point’ allows changing the desired speed of vehicles at certain points on the road network. In other words, ‘desired speed decision points’ have the same function as the variable message signs (VMSs) in the real VSL system. Every compliant vehicle which crosses the speed decision points will get a new desired speed equivalent to the VSL with a small stochastic variation (± 7km/h) while non-compliant vehicles ignore the VSL and retain the speed assigned to them from the base-model speed distribution.

Safety benefits of assisting normal drivers using VSL

Table 3 shows a summary of vehicle conflicts for different levels of driver compliances during heavily congested traffic conditions (Level of Service of D). Every change in the count of vehicle conflicts was found to be statistically significant and the percentage reduction in rear-end and lane-changing conflicts were nearly of equal amount. It can be inferred that VSL has safety benefits which is confirmed by the reduction in the count of vehicle conflicts ranging from 37% for low level of compliance to as much as 75% for very high compliance level by drivers. Employing equation (4), this would mean a reduction of 22% to 44% in the expected crashes on the facility. This suggests that VSL has a potential to reduce inappropriate maneuvers drivers practice to proceed in the traffic, like short headways and frequent change of lanes. In addition, the rate of reduction in lane-changing conflicts was of a constant amount all the way from low to very high compliance levels which suggests that it is linearly correlated to driver compliance levels. However, the rate of reduction in rear-end conflicts was very sharp in the transition from low to medium compliance levels. This suggests that VSL is beneficial even at small scale compliance levels, in this case medium compliance level. Moreover, it is found that VSL with a very high level of compliance has double safety benefits than low compliance level.

TABLE 3 - Safety benefits of VSL for different levels of driver compliances under heavily congested traffic conditions (all with replications = 10, degrees of freedom = 18, alpha = 0.05 and t-critical = 1.734)

Level of compliance by drivers	Conflict Types	Mean without VSL	Mean with VSL	t value	p value	Significant	Mean Difference	Percentage increase
Low (25%)	Rear-end	72.60	42.70	3.934	4.86E-04	YES	29.90	-41%
	Lane-changing	68.80	46.10	6.927	8.90E-07	YES	22.70	-33%
	Total	**141.4**	**88.80**	**6.817**	**1.11E-06**	**YES**	**52.60**	**-37%**
Medium (50%)	Rear-end	72.60	21.80	7.534	2.80E-07	YES	50.80	-70%
	Lane-changing	68.80	33.20	10.63	<1.0E-08	YES	35.60	-52%
	Total	**141.4**	**55.00**	**11.22**	**<1.0E-08**	**YES**	**86.40**	**-61%**
High (75%)	Rear-end	72.60	19.30	7.785	1.80E-07	YES	53.30	-73%
	Lane-changing	68.80	24.00	14.01	<1.0E-08	YES	44.80	-65%
	Total	**141.4**	**43.30**	**13.19**	**<1.0E-08**	**YES**	**98.10**	**-69%**
Very High (100%)	Rear-end	72.60	16.80	8.793	3.00E-08	YES	55.80	-77%
	Lane-changing	68.80	18.30	16.67	<1.0E-08	YES	50.50	-73%
	Total	**141.4**	**35.10**	**15.32**	**<1.0E-08**	**YES**	**106.30**	**-75%**

The safety benefits of VSL during lightly congested (Level of Service of C) and non-congested (Level of Service of B) traffic conditions were also investigated. The results show that application of VSL during lightly congested traffic conditions was demonstrated by reduction in conflicts which amounted into 27% for low compliance levels, 46% for medium compliance level, 50% for high compliance levels and 61% for very high compliance levels. These reductions in simulated vehicle conflicts were equivalent to reduction of 7% to 13% in expected crashes. Similarly, application of VSL during non-congested traffic conditions resulted into no reduction in simulated vehicle conflict for low compliance levels while there was a reduction of 25% during medium compliance levels, 44% during high compliance as well as 49% during very high compliance levels. These reductions in simulated vehicle conflicts were found to be equivalent to a maximum reduction of 12% in the frequency of the expected crashes.

Operational benefits of assisting normal drivers using VSL

The operations of motorway traffic with VSL during heavily congested traffic conditions are presented in terms of travel time. There appears to be no statistically significant benefit or loss in operations of the motorway due to application of VSL under heavily congested traffic conditions. This was in agreement with the findings of Abdel-Aty et al. (2006a) that VSL does not relieve congestion. However, uniform headways and reduction in frequency of lane-changes (as evidenced from Table 3) are signs of stable and harmonized traffic flow due to VSL. Given the fact that safety and efficiency of roads are interdependent, it has to be noted that the safety improvements will positively affect the operations of the motorway by at least reducing the occurrence of crash related non-recurrent congestions. As a result, there exists an underlying operational gain from the safety benefits of VSL, for example travel time regularity or trip reliability even during heavily congested traffic conditions. Similarly, the operational benefits during lightly congested traffic conditions were found to be of a maximum value relative to other traffic conditions. These benefits were reduction in travel time ranging from 2% for low compliance levels to as much as 16% for very high compliance levels. On the other hand, the efficiency in traffic operations during non-congested traffic condition amounted to only 1% savings in travel time under low level of compliance and 6% under very high compliance level. It can be said that VSL had a potential to promote the operations of motorway traffic during all traffic conditions and most importantly during very high compliance levels.

5. CONCLUSION AND RECOMMENDATIONS

This study has examined the safety and operational benefits of traffic management strategies that correspond to high-risk drivers and normal, i.e. by limiting the driving degree of freedom of high-risk drivers and application of VSL to assist normal drivers. The proposed management strategies were evaluated using simulation-based analysis for their potential benefits on safety and operations of motorway traffic. Safety benefits were quantified by correlating the count of simulated vehicle conflicts with the frequency of real crashes and operational benefits were quantified by noting the reduction in travel time to traverse the simulated network. The findings of this research work can be summarized as follows:

- Limiting the driving freedom of high-risk drivers of proportions of 4%, 8% and 12% of total drivers on the network resulted into reduction of expected crashes by 21%, 46% and 68% during heavily congested traffic conditions; 8%, 16% and 26% during lightly congested traffic conditions as well as 4%, 12% and 17% during non-congested traffic conditions.
- Another benefit of limiting the driving degree of freedom of high-risk drivers is improvement in traffic operations which amounted to savings of 1% in travel time during heavily congested, lightly congested and non-congested traffic conditions for all proportions of high-risk drivers considered, i.e. 4%, 8% and 12%.
- VSL has a potential to promote both safety and operations of motorways under all traffic condition. This confirms that the safety benefits of VSL are not at the expenses of increase in travel time.
- The magnitude of the safety and operational benefits of VSL are highly dependent on the level of drivers' compliance. This suggests that the incentive for deployment of good enforcement mechanism is prominent to achieve higher levels of compliance and attain the optimum benefits from the system.

- The safety benefits of VSL are highest during highly congested traffic conditions (up to 44% reduction in expected crashes). The operational benefit of VSL is at its highest level during lightly congested traffic conditions (up to 16% reduction in travel time) which suggests that the system has to be switched on long before rush hours.

The findings imply that there exist substantial safety and operational benefits from introducing a traffic management strategy that correspond to different segment of driver, i.e. limiting the driving degree of freedom of high-risk drivers and assisting normal drivers using VSL. The limitation of this research is that human behavior is a result of multiple factors interacting with each other which makes it difficult in terms of modeling it or expressing it with a few parameters. Thus, future works may focus on use of driver simulator or naturalistic driving studies for real input of high-risk driving error and most importantly to confirm the simulation-based results in a realistic driving environment. Another limitation is the concerns of individual privacy, enforcement methods and the trade-offs between these benefits and social, legal and institutional implications of limiting the driving degree of freedom of high-risk drivers and enforcing the VSL.

6. REFERENCES

AAA (2009). *Aggressive Driving: Research Update*. AAA Foundation for Traffic Safety, Washington, D.C.

Abdel-Aty, M., Dilmore, J. and Hsia, L. (2006a). Applying Variable Speed Limits and the Potential for Crash Migration. *Transportation Research Record*, 1953, pp. 21–30.

Archer, J., and Kosonen, I. (2000). The Potential of Micro-Simulation Modeling in Relation to Traffic Safety Assessment. *Proceedings of 12th European Simulation Symposium*, Hamburg.

Boyce, T. (1999). *Identifying Functional Relationships in Driver Risk Taking: An Intelligent Transportation Assessment of Problem Behavior and Driving Style*. PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg.

Brookhuis, A., De Waard, D. and Fairclough, H. (2003). Criteria for driver impairment. *Ergonomics*, 46(5), 433- 445.

Broughton, P. And Stradling, S. (2005). *Why ride powered two wheelers? In Behavioral Research in Road Safety 2005: Fifteenth Seminar*. London: Department for Transport, 68-78.

Chitturi, M., and Benekohal, R. (2008). Calibration of Vissim For Freeways. *Paper presented at the 87th annual meeting of the Transportation Research Board*, Washington D.C.

Evans, L. (1991). *Traffic safety and the driver*. New York: Van Nostrand Reinhold.

Evans, L. (2004*). Traffic Safety*. MI; Science Serving Society, Bloomfield Hills.

Fudala, N., and Fontaine, M. (2010). Interaction between System Design and Operations of Variable Speed Limit Systems in Work Zones. *Transportation Research Record*, 2169, 1–10.

Fuller, R. (2000). The Task-Capability Interface model of the driving process. *Recherche Transports Securite*, 66, 47–57.

Fuller, R. (2005). Towards a General Theory of Driver Behavior. *Accident Analysis and Prevention*, 37, pp. 461–472.

Fuller, R., (2007). Risk as feelings: implications for safe driving practice. *Engineers Ireland, 22 Clyde Road*, Dublin. < acceced on March 22nd, 2012 http://www.engineersireland.ie/EngineersIreland/media/SiteMedia/groups/societies/roads-tranport/Risk-as-feelings-implications-for-safe-driving-practice.pdf?ext=.pdf

Fuller, R., Bates, H., Gormley, M., Hannigan, B., Stradling, S., Broughton, P., Kinnear, N. and O'Dolan, C. (2008). *The Conditions for Inappropriate High Speed: A Review of the Research Literature from 1995 to 2006*. Road Safety Research Report No. 92. London: Department for Transport.

Fuller, R., Santos, J. (2002). Psychology and the highway engineer. In: Fuller, R., Santos, J.A. (Eds.), *Human Factors for Highway Engineers*. Pergamon, pp. 1–10.

Gettman, D. and Head, L. (2003). Surrogate Safety Measures from Traffic Simulation Models. *Transportation Research Record*, 1840, 104-115.

Gettman, D., Pu, L., Sayed, T., and Shelby, S. (2008). *Surrogate Safety Assessment Model and Validation: Final Report*. Federal Highway Administration, FHWA-HRT-08-051. Washington D.C.

Guo, F. and Fang, Y. (2012). Individual Driver Risk Assessment Using Naturalistic Driving Data. *Accident Analysis and Prevention*, (In press, Available online 9 July 2012).

Habtemichael, F. and Picado-Santos, L. (2012a). Safety Evaluation of Aggressive Driving on motorways Through Microscopic Traffic Simulation and Surrogate Measures. *Paper presented at the 91th annual meeting of the Transportation Research Board*, Washington D.C.

Habtemichael, F. and Picado-Santos, L. (2012b). The Need for Transition from Macroscopic to Microscopic Traffic Management Schemes to Improve Safety and Mobility. *Procedia of Social and Behavioral Science*, 48, pp. 3018-3029.

Habtemichael, F. and Picado-Santos, L. (2013a). Sensitivity Analysis of VISSIM Driver Behavior Parameters on Safety of Simulated Vehicles and their Interaction with Operations of Simulated Traffic. *Paper presented at the 92nd annual meeting of the Transportation Research Board*, Washington D.C.

Habtemichael, F. and Picado-Santos, L. (2013b). Safety and Operational Benefits of VSL under Different Traffic Conditions and Driver Compliance Levels. *Transportation Research Record*. (Accepted for publications and currently in press).

Harder, K., Kinney, T., and Bloomfield, J. (2008). Psychological and Roadway Correlates of Aggressive Driving. *Intelligent Transportation Systems Institute, Center for Transportation Studies*, Minneapolis.

Harré, N. (2000). Risk Evaluation, Driving, and Adolescents: A Typology. *Developmental Review*, 20, 2, pp. 206–226.

Harvey, C., Jenkins, D. and Sumner, R. (1975). Driver Error Supplementary Report 149 UC. *Transport and Road Research Laboratory*, Crowthorne.

Holm, P., Tomich, D., Sloboden, J., and Lowranc, C. (2007). *Traffic Analysis Toolbox Volume IV: Guidelines for Applying CORSIM Microsimulation Modeling Software*. Federal Highway Administration, Report No. FHWA-HOP-07-079, Washington D.C.

Horne, J. and Reyner, L. (1999). Vehicle Accidents Related to Sleep: A Review. *Occupational and Environmental Medication*, 56, 289–294.

Hutabarat, R., Lam, J., and Lawrence, M. (2004). *Remedies for Driver Error: Final Report 567*. Federal Highway Administration, Arizona Department of Transportation, Report No. FHWA-AZ-04-56, Phoenix.

Klauer, S.G., Dingus, T. A., Neale, V. L., Sudweeks, J.D., and Ramsey, D.J. (2006). *The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car*

Naturalistic Driving Study Data. Virginia Tech Transportation Institute, Report No. DOT HS 810 594, Virginia.

Lownes, N. and Machemehl, R. (2006a). Sensitivity of Simulated Capacity to Modification of VISSIM Driver Behavior Parameters. *Transportation Research Record*, 1988, 102–110.

Lownes, N., and Machemehl, R. (2006b). VISSIM: a multi-parameter sensitivity analysis. *Proceedings of Winter Simulation Conference*, Monterey, 1406-1413.

Menneni, S., Sun, C., and Vortisch P. (20080). Microsimulation Calibration Using Speed–Flow Relationships. *Transportation Research Record*, 2088, 1-9.

Minderhoud, M., and Bovy, P. (2001). Extended Time to Collision Measures for Road Traffic Safety Assessment. *Accident Analysis and Prevention*, 33, 89–97.

Musselwhite, C. (2006). Attitudes towards vehicle driving behavior: Categorising and contextualising risk. *Accident Analysis and Prevention*, 38, pp. 324–334.

Nezamuddin, N., Jiang, N., Ma, J., Zhang, T., and Waller, T. (2011). Active Traffic Management Strategies: Implications for Freeway Operations and Traffic Safety. *Paper presented at the 90th annual meeting of Transportation Research Board*, Washington D.C.

Ozbay, K., Yang, H., Bartin, B., and Mudigonda, S. (2008).Derivation and Validation of New Simulation-Based Surrogate Safety Measure. *Transportation Research Record*, 2083, 105–113.

Park, B., and Schneeberger, J. (2003). Microscopic Simulation Model Calibration and Validation Case Study of VISSIM Simulation Model for Coordinated Actuated Signal System. *Transportation Research Record*, 1856, 185-92.

PTV. (2009). *Vissim 5.30 User Manual*. Planung Transport Verkehr AG (PTV), Karlsruhe.

Reason, J. (1990). *Human Error*. Cambridge University Press: New York.

Rolls, G. and Ingham, R. (1992). *Safe and Unsafe: A comparative study of younger male drivers.* AAA Foundation for Road Research, Basingstoke.

Sarkar, S., Martineau, A., Emami, M., Khatib, M., and Wallace, K. (2000). Aggressive Driving and Road Rage Behaviors on Freeways in San Diego, California: Spatial and Temporal Analyses of Observed and Reported Variations. *Transportation Research Record*, 1724, 7–13.

Stanton, N. and Salmon, P. (2009a). Driver Error and the Implications for Intelligent Transport Systems Design. 1*6th ITS World Congress and Exhibition on Intelligent Transport Systems and Services*, Stockholm.

Stanton, N., and Salmon, P. (2009b). Human Error Taxonomies Applied to Driving: A Generic Driver Error Taxonomy and Its Implications for Intelligent Transport Systems. *Safety Science*,47, 227-237.

Sun, D., Benekohal, R. and Estrasa, H. (2008). “Comparative Analysis of the Attitude and Behavior of Young Drivers' Use of Two-way Two-lane Highways.” *Journal of Advances in Transportation Studies*, 15(B), 75-84.

Tarko, A., Davis, G., Saunier, N., Sayed, T. and Washington, S. (2009). *White Paper Surrogate Measures of Safety.* Transportation Research Board, ANB20 (3) Subcommittee on Surrogate Measures of Safety.
<https://wiki.umn.edu/pub/TRB_ANB203/WebHome/Surrogate_Measures_of_Safety_-_A_White_Paper_2009.pdf > [visited on June, 2012]

WHO (2004). *World report on road traffic injury prevention*. World Health Organization, WHO, Geneva.