Predicting the effect of various ISA penetration grades on pedestrian safety by simulation

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Abstract

Intelligent speed adaption (ISA) is one type of vehicle-based intelligent transportation systems (ITS), which warns and regulates driving speed according to the speed limits of the roads. Early field studies showed that ISA could reduce general mean speed levels and their variances in different road environments. This paper studies the effects of various ISA penetration grades on pedestrian safety in a single lane road. A microscopic traffic simulation tool, TPMA, was further developed and used to implement different ISA penetration grades. Momentary spot speed and traffic flow data are first logged in the traffic simulation for later prediction of pedestrian safety. Then a hypothetical vehicle–pedestrian collision model is extended from early researches in order to estimate two safety indicators: probability of collision, and risk of death. Finally, Monte Carlo method is applied iteratively to compute those safety indices. The computational result shows that raising ISA penetration in traffic flow will reduce both the probability of mid-block collision between vehicle and pedestrian and the risk of death in the collision accidents. Furthermore, the decrease of the risk of death will be more prominent than that of the collision probability according to this method.

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Keywords: ISA penetration; Pedestrian safety; Collision model; TPMA simulation; Monte Carlo experiment

1. Introduction

Safety planning has been a duty of transportation engineers for a long time. Speed control is one of the most important areas of transport safety because of the observed correlations between speed level and accident statistics (Lind, 1997; Archer, 2005). Traditionally, inroad speed limitation has been the main means of speed regulation. Speed limit displays the highest permitted speed on normal roads and under common conditions. However, it is not appropriate and flexible enough for many situations where a variation of speed limits is needed, e.g. the changes of the weather, time and congestion situation. Recent advances in information and telecommunication technology offer a broader possibility of influencing speed dynamically by intelligent speed adaption (ISA). There are several kinds of preliminary or experimental ISA products. In-vehicle speed limiter system has been adopted in the ISA evaluation in several European countries. The system produces a counter-force in the accelerator pedal when the speed limit coded in a digital map using the GPS system is reached but can be overridden by pressing the pedal with extra efforts sufficient to deter drivers from speeding.

1.1. ISA effects

Field studies of ISA had been done in Sweden, the Netherlands, and Spain in order to test real ISA effects and reveal possible regional differences within European countries. In Sweden, a large scale trial with the speed adaption system was implemented in Lund between 1999 and 2002 where around 300 vehicles were equipped with speed limiters. According to the study by Várhelyi and Mäkinen (2001) and Hjalm Dahl et al. (2002), ISA had the greatest effect under free flow driving conditions while having a smaller effect in the congested mode. The real effects of ISA in those studies can be sum-

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behavior in Sweden (Hjälmdahl and Várhegyi, 2004) showed drivers would accept the equipment voluntarily in their cars. Accepted ISA as a driver-operated system and half of the drivers caused by the ISA; the majority of the subjects reported that the equipment remained in their cars longer between 30 and 50 km/h, a slightly higher number of short time headways suggested less safe car-following behavior; slightly increased travel time and increased frustration and stress for the drivers caused by the ISA; the majority of the subjects accepted ISA as a driver-operated system and half of the drivers would accept the equipment voluntarily in their cars.

A recent study of the long-term effect of ISA on driving behavior in Sweden (Hjälmdahl and Várhegyi, 2004) showed that drivers who had used the system on their own cars for more than 6 months had improved their behavior towards other road users: they had a yielding behaviors correct to a higher degree and were more likely to give pedestrians the right of way at zebra crossing; moreover, the time gap between ISA vehicle and the vehicle in front increased slightly. Hence, the effects of ISA are not only reflected in the short term speed reduction but also revealed in the long-term behavior adaptation. However, this research was based on a survey of 28 subjects who volunteered to use the ISA equipment. The result would be more convincing if the study could include both volunteers and mandatory users, especially people who tended to reject the system during their test drive. In addition, it would be interesting to see how the behavior was evolving with the time. All of these will provide crucial information on how to generalize the ISA effects on driving behavior.

Until now, only the studies of ISA effect on individual driver are reviewed and our focus has been mainly on the driving behavior aspect. Few studies have been done on evaluating effects of a high ISA penetration grade, as it can hardly be investigated by field trials. Simulation might be the only available means for the study of various penetration grades of ISA vehicles. In our early study using microscopic simulation (Ma et al., 2004), the ISA effect on free flow speed reduction was modelled as a change of the desired speed distribution. It was assumed that the car following behaviors would not be significantly affected by the application of ISA systems. The result of the simulation agreed with our expectation of the ISA effect on the reduction of instant speed levels and variations in different speed limits, traffic flow levels, ISA percentages and locations. However, the changes on the headway distribution in the simulation were not statistically significant, which makes the direct correlation between desired speed reduction and headway distribution still a question.

1.2. Pedestrian risk

Vehicle pedestrian conflict is an important aspect of road safety planning. Historical accident records show that a heedless person dashing out into the road and being injured or even killed is one of the most frequent pedestrian accident types (Stutts et al., 1996) and the unprotected children stand for a big portion of those victims. On the other hand, the pedestrian’s gap acceptance error is seldom observed as an accident cause since people do not intend to cross the road when there is a queue of vehicles. Hence, an individual free vehicle on an uncongested road is more dangerous from the pedestrian safety perspective (Pasanen and Salmivaara, 1993).

A number of indicators have been derived and used in pedestrian safety planning. Probability of a collision accident is an indicator used to evaluate traffic calming measures by Davis (2000). Moreover, the distribution of the collision speed between vehicle and pedestrian was adopted in the evaluation of the severity of the accident. Both of the factors were estimated using a hypothetical collision model. Risk of death is a factor developed to understand the influence of the collision speed (Ashton, 1982). A mathematical model was derived by Ashton to estimate the influence of collision speed on the probability of death when a random pedestrian appeared on the road independent of the location and the speed of coming vehicles. Pasanen and Salmivaara (1993) further derived the relation between instant driving speed and risk of death. The regression result showed a potential relation between instant driving speed and probability of death, e.g. a driving speed of 50 km/h increases the risk of death almost eight times compared to a speed of 30 km/h, and almost 2.6 times compared to a speed of 40 km/h; when the driving speed is below 30 km/h, the probability of death is smaller than 0.05.

2. Objective

The main purpose of this research is to develop a method to quantitatively evaluate how different ISA percentages in traffic flow will affect pedestrian safety expressed by two indicators: probability of collision and risk of death. Risk of death can be considered as an indicator for the measure of accident severity. Both of these indices can be estimated from instant speed and traffic flow data using an offline simulation procedure based on a collision model. To investigate the effect of different ISA penetration grades, microscopic simulation is used to generate the real data. Similar to the previous study (Ma et al., 2004), the difference between ISA and non-ISA vehicles in traffic simulation is reflected in the variation of the free flow desired speeds. Fig. 1 illustrates the procedures in predicting the pedestrian safety at different ISA penetration levels.

3. Method

In this section, the vehicle pedestrian collision, in which a vehicle hits a dart-out careless pedestrian, will be modelled at first in order to derive the method to compute the collision probability $p_c$ and the distribution of the possible collision speed $v_c$ in this mid-block accident. The computation of the safety indices above is based on the spot speed and traffic flow data from the simulation with different ISA penetration.
grades. The simulation tool, TPMA, will be introduced to explain how the ISA vehicle is modelled.

3.1. The collision model and basic assumptions

To derive the safety indicators analytically, a vehicle–pedestrian collision model is built with extensions of the previous studies (Davis, 2000) and (Pasanen and Salmivaara, 1993). The model is illustrated in Fig. 2. It is assumed that the vehicle has an initial speed \( v \) and a distance \( d_v \) from the conflict zone when the driver perceives the unwary pedestrian who has a speed of \( v_p \) and a distance \( d_p \) from the conflict zone.

To simplify the situation, we assume here that the pedestrian will accept the headway \( t_v = \frac{d_v}{v} \) anyhow because of his unwariness. When \( t_v > t_{cross} \), the vehicle is so far away that the pedestrian can cross through the street without any collision. When \( t_v < t_p \), the vehicle will arrive at the conflict zone before the pedestrian and the pedestrian is assumed to stop before hitting the vehicle. In both situations above, the accident can be avoided without any necessary reaction from the driver. However, the pedestrian will be exposed to the danger when

\[
\frac{d_p}{v_p} = t_p < t_v < t_{cross} = \frac{d_p + w}{v_p}.
\]

Therefore, the driver needs to decelerate to avoid an accident. It is assumed that the driver will brake with a constant deceleration rate \( \alpha_{dec} \) and the driver needs a reaction time \( t_r \) to make his decision. When

\[
t_v < t_r,
\]

the driver does not have enough time to react and brake. The vehicle will hit the pedestrian with the speed \( v \). When \( t_v > t_r \), a potential collision occurs only if the vehicle cannot stop before hitting the conflict zone, which can be defined as

\[
d_v = \frac{v^2}{2\alpha_{dec}} + v_t t_r.
\]

Combining Eqs. (1) and (3), the potential collision happens only if

\[
\max(t_p, t_r) < t_v < \min(t_{cross}, t_{stop}).
\]

where \( t_{stop} = \frac{v}{2\alpha_{dec}} + t_r \) and \( t_p \) and \( t_{cross} \) are given by Eq. (1). Nevertheless, Eq. (4) cannot ensure an accident since with braking actions the time interval to collision zone is extended to:

\[
t_v' = \frac{v_v - v_v}{\alpha_{dec}} > t_r
\]
where \( v_c = \sqrt{\frac{c^2}{2}} - \frac{2w_{en}}{v_c} \) is the collision speed. Another condition which needs to be fulfilled for an accident to happen is:

\[
\frac{d_0}{t_p} + \frac{w}{v_p} + \frac{v_c}{\sqrt{2}} \leq t_{cross} - t_{cross}
\]  

(6)

If the variables defined in the model can be determined, we can estimate the probability of collision by a summary of the cases from (1) to (6)

\[
\begin{align*}
P(t_p) &= \text{Prob}(t_p < t_v < \min(t_v, t_{cross})) \\
&+ \text{Prob} \left[ \max(t_v, t_p) < t_v < \min(t_{cross}, t_{stop}) \land \frac{d}{t_p} < t_{cross} \right] \\
&\quad \text{Prob} [\mathcal{c}(d, v_p)] \\
&\quad \text{Prob} [\mathcal{c}(v_p, t_p)] \\
&\quad \text{Prob} [\mathcal{c}(v_p, t_v)] \\
&\quad \text{Prob} [\mathcal{c}(t_v, t_p)]
\end{align*}
\]  

(7)

3.2. Estimation of the pedestrian safety indicators

In principle, all the variables referred in the Eq. (7) should be treated as random variables though many studies only adopted a subset of the variables to be uncertain. In the early study by Davis (2000), a conflict point was considered, i.e. \( w = 0 \) or \( t_p = t_{cross} \) and the pedestrian was assumed to stop when he or she arrived at the conflict point before the coming vehicle. Only the speed of the vehicle \( v_c \) and distance headway \( d \) were treated as random whereas other variables were assumed to be deterministic. Based on the assumption that the vehicle arrival converges to a Poisson process, i.e. the distance headway \( d \) is exponentially distributed when the traffic flow level is low, the probability that the vehicle collided with the pedestrian was derived as

\[
P_{vd} = \text{Prob}(v_c \leq d < \frac{c^2}{2w_{en}} + v_c t_p | d_p, v_p, w_{en}, t_p) \text{pdf}(v_c)
\]  

(8)

where \( \text{pdf}(v_c) \) is the probability density function of the vehicle speed, \( b = \max(0, 2w_{en}, d_p/t_p - t_p) \) and \( \rho \) is the traffic density (vehicles per meter) on the road. If the distribution \( \text{pdf}(v_c) \) is known, the Eq. (8) can be estimated numerically.

In our study, the conflict point is extended to a zone where the pedestrian might be run over by the passing vehicle and all the variables are assumed to be random, resulting in the difficulty to express the probability of collision as an Eq. (8).

Therefore, the Monte Carlo method (Law and Kelton, 2000) is applied to estimate the probability of collision and the distribution of the collision speed \( \hat{d}(v_c) \). Table 1 summarizes the distributions of the random variables used in the simulation model of vehicle pedestrian collision. Instead of using the deterministic headway from the simulation, it is drawn from the displace double negative exponential (DDNE) distribution whose probability density function is represented by:

\[
P_d(t) = \left\{ \begin{array}{ll}
\phi_1 e^{-(t-\phi_0)/\phi_1} + (1 - \phi_1) e^{-(t-\phi_0)/\phi_2} & t \geq \phi_0 \\
0 & 0 < t < \phi_0
\end{array} \right.
\]  

(9)

This distribution was proposed as one type of composite model approaches (e.g. May, 1990, Ch. 2). A large amount of urban traffic data for different flow levels had been collected in order to calibrate the headway distribution of the DDNE form (Griffiths and Hunt, 1991). The driver reaction time \( t_r \) is assumed to be lognormal distributed with mean and S.D. referred from an early study by Triggs and Harris (1982). The pedestrian walk speed and starting position is assumed according to early studies (e.g. Knoblauch et al., 1996). The distribution of the width of the collision zone is approximated by the width of vehicles. Some of the information above may not be accurate but the result of our experiments seems not strongly affected by those elements when they are within a reasonable scope.

At last, using the mathematical relation between the probability of death \( p_d \) and collision speed developed by Ashton (1982):

\[
p_d(v_c) = \frac{1.027}{1 + 37e^{0.015c^2}} - 0.027
\]  

(10)

an indicator of the probability of death of the dart-out pedestrian can be estimated by

\[
\text{R}_d = \int_{v_c} \hat{d}(v_c) |p_d(v_c)|dv_c.
\]  

(11)

With the result from the replicated Monte Carlo experiments, the risk of death can be approximately computed by:

\[
\hat{R}_d = \frac{1}{N} \sum_{i=1}^{N} \hat{R}_d(v_i).
\]  

(12)

Table 1

A summary of the distribution type and parameters of the random variables for the Monte Carlo simulation of vehicle–pedestrian collision

<table>
<thead>
<tr>
<th>Variables</th>
<th>Distribution type and parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle time headway (t_v)</td>
<td>DDNE distribution (d, ( \lambda_1, \lambda_2 ))</td>
</tr>
<tr>
<td>Vehicle speed (v_c)</td>
<td>Deterministic from the log data of simulation runs</td>
</tr>
<tr>
<td>Driver reaction time (t_r)</td>
<td>Lognormal distribution (( \mu = 1.2, \sigma^2 = 1 ))</td>
</tr>
<tr>
<td>Emergency braking rate (( a_{eb} ))</td>
<td>Truncated normal distribution (( \mu = 5.5, \sigma^2 = 1 ), minimum=3.5, maximum=7.5)</td>
</tr>
<tr>
<td>Pedestrian speed (v_p)</td>
<td>Uniform distribution (2, 2.3)</td>
</tr>
<tr>
<td>Pedestrian starting position (d_p)</td>
<td>Truncated normal distribution (( \mu = 1.5, \sigma^2 = 1 ), minimum=0.5)</td>
</tr>
<tr>
<td></td>
<td>Uniform distribution (1, 5)</td>
</tr>
</tbody>
</table>
3.3. Modelling of ISA in the microscopic simulations

To predict the pedestrian safety under various ISA penetration grades, the real time spot speed and traffic flow data have to be generated by simulation. TPMA is a microscopic traffic simulation tool, which is developed based on an early version of HUTSIM (Kosonen, 1999). It uses the object oriented software design approach and is implemented using Borland Delphi language (Ma, 2005). The elementary models of TPMA, including car following and lane changing, are at the moment inherited from HUTSIM, and were calibrated using a large amount of data collected from Swedish road networks in the early TPMA project (Kosonen et al., 2001). In the TPMA model, each vehicle driver is given a random number from a predetermined distribution such as normal distribution, and this number can be translated as the aggressiveness grade of the driver. With this random number, a driver will obtain his free flow desired speed from the distribution used. In this study, ISA vehicle is modelled as different from the common vehicle only in its free flow desired speed distribution. In the implementation, a dynamic speed adaption flag object for a certain vehicle type is created and connects to a certain road segment. This speed adaption object will trigger repeated sampling of the desired speed according to the random number that the passing vehicles get at their generation and the newly defined desired speed distribution. Fig. 3 displays how the microscopic simulation TPMA looks like and how the vehicle chooses a new desired speed when meeting a speed flag object. Hence, it is possible for ISA and non-ISA vehicle to choose their own desired speed at each road link according to the predefined free flow desired speed distributions for each type of vehicle.

4. Results

Dozens of runs of simulation were done for this study using TPMA in a simple network composed of single lane roads in order to generate the traffic data under the combination of different speed limits, ISA penetration grades and flow levels. The streets with 30 and 50 km/h speed limits where the vehicle pedestrian accidents mostly happen are of interest in our research. According to the early study (Hjalmåndahl et al., 2002), the ISA effect on the free flow speed at the same speed limit may vary at different roads and traffic conditions, but the summary of the ISA effect is based on an aggregation of the observed field data in the category of different speed limits. Although, the aggregated speed reductions are significant for all the speed limits, the streets with traffic conditions that make the mean speed always less than the speed limit are also included. In those streets, the speed limiter is obviously less or even not useful. Adopted in our simulation study are those speed distributions estimated on streets under normal traffic conditions which may make drivers intend speeding, i.e. there is no congestion or interference from many intersections or roundabouts. Hence, the speed limiter can always show its effects on the restriction of speeding. Table 2 shows the typical values that we used in the simulation. The traffic data is collected in simulation by output detector objects at the downstream of the speed flag objects where the ISA and non-ISA have

![Fig. 3. Modelling of ISA effect on free flow speed level in TPMA.](image-url)
Table 2: Mean and S.D. of the vehicle speed at different speed limits with or without ISA

<table>
<thead>
<tr>
<th>Road type (km/h)</th>
<th>Mean speed (km/h)</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-ISA</td>
<td>ISA</td>
<td>Non-ISA</td>
</tr>
<tr>
<td>50</td>
<td>38.74</td>
<td>51.13</td>
</tr>
<tr>
<td>30</td>
<td>33.52</td>
<td>28.15</td>
</tr>
</tbody>
</table>

Fig. 4. The effect of ISA penetration on the probability of collision between vehicle and pedestrian.

already adapted to their new desired speed on the street. The distance between the detector and the speed flag is 500, 1000, and 1500 m, respectively. Meanwhile, different traffic flow volumes, from 50 to 400 veh/h, are applied. The higher flow level is not considered here since the pedestrian is more possible to be alert and the signal control may also be settled in streets with a heavy traffic.

Table 3 shows the results for various ISA penetration levels at a typical 50 km/h road after 1000 replications of the Monte Carlo experiments of vehicle pedestrian conflict. It is worth to mention that the numerical values estimated for probability of collision and death in the table are based on the assumption that each vehicle will meet a careless dart-out pedestrian. But in reality meeting a dart-out pedestrian is an event of small probability for drivers, which depends on time, weather, traffic conditions and many other local factors. For example, the probability to meet an unwary dart-out pedestrian is normally higher in the school area than other areas. Therefore, the danger in terms of probability of collision and death is overstated by a certain factor but traffic planners can modify them by considering the probability of meeting a dart-out heedless pedestrian estimated locally. Nevertheless, the computational results in the table show the direct relation between ISA penetration and the risks of collision and death. When ISA penetration is increased, the mean of the probability of vehicle-pedestrian collision tends to decrease for each certain traffic flow level and each location though the reduction is slight. Using statistical t-tests, all the reductions are significant at 99% level. Fig. 4 illustrates the relation between ISA penetration grade and probability of collision at 100 and 200 veh/h. In comparison with the slight decrease of the probability of collision, the computational result of the risk of death for the heedless pedestrian estimated by Eq. (12) indicates a conspicuous reduction of the accident severity with the addition of ISA vehicle percentage in the traffic flow. Fig. 5 illustrates the relation between ISA penetration and risk of death. For 30 km/h speed limit, the

Table 3: Mean probability of collision (%) (upper) and the risk of death (%) (lower) for different traffic flow, ISA penetration grades, and locations at 50 km/h

<table>
<thead>
<tr>
<th>Traffic flow</th>
<th>0%</th>
<th>30%</th>
<th>50%</th>
<th>70%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 m</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
</tr>
<tr>
<td>1000 m</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
</tr>
<tr>
<td>1500 m</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
<td>1.097</td>
</tr>
</tbody>
</table>

or 0.207 (1500 m). In comparison with the slight decrease of the probability of collision, the computational result of the risk of death for the heedless pedestrian estimated by Eq. (12) indicates a conspicuous reduction of the accident severity with the addition of ISA vehicle percentage in the traffic flow. Fig. 5 illustrates the relation between ISA penetration and risk of death. For 30 km/h speed limit, the
computational results are consistent with those at 50 km/h, i.e. a slight decrease of the probability of collision and a distinct reduction of the risk of death when the ISA penetration raises.

Besides the effect of ISA penetration, the distance from the origin of speed adaption shows its direct relation with pedestrian safety. In Fig. 4, the probability of collision decreases with the increasing distance between the current vehicle position and the speed adaptation flag, although this tendency fades out at the sparse traffic flow for example 100 veh/h. From Fig. 5 it is not difficult to tell that the influence of the distance is more pronounced on risk of death than on probability of collision. In general, the plateau effect becomes more evident when the car travels further from the speed adaption origin, i.e. a vehicle with higher desired speed will be finally blocked by a vehicle with slower desired speed on a single lane road. Hence, the total speed level tends to slow down and converges to a steady state when the distance is far enough.

Lastly, it is also noticeable that with the augment of traffic flow both the probability of collision and the risk of death for a dart-out pedestrian increase under the same ISA penetration. This outcome seems quite straightforward since the increase of the vehicle arrival frequency boosts up the probability that collision happens. The simulation result may serve as numerical flesh to the bone of the logic behind.

5. Summary and conclusions

Intelligent speed adaption has become an intriguing technology for future speed management due to ISA's potential effect on global speed reduction though its long term and general effect on the driver behaviors, traffic characteristics and the consequent safety are still under investigation. This paper shortly introduces recent study results on ISA mainly in Swedish roads. With a basic assumption that the ISA will raise the free flow speed distribution of the driver, ISA vehicle is modelled in a traffic simulation environment, TPMA, in order to generate the traffic data under different ISA penetration grades. By applying a vehicle pedestrian collision model extended from the early studies and the iterative Monte Carlo simulations of the conflict, the safety effect of ISA penetration is evaluated by estimation of the probability of collision and the risk of death when the ISA penetration grades. By applying a vehicle pedestrian collision model extended from the early studies and the iterative Monte Carlo simulations of the conflict, the safety effect of ISA penetration is evaluated by estimation of the probability of collision and the risk of death. From Fig. 5 it is not difficult to tell that the influence of the distance is more pronounced on risk of death than on probability of collision. In general, the plateau effect becomes more evident when the car travels further from the speed adaption origin, i.e. a vehicle with higher desired speed will be finally blocked by a vehicle with slower desired speed on a single lane road. Hence, the total speed level tends to slow down and converges to a steady state when the distance is far enough.

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