SELECTION OF CONTROL SPEEDS IN DYNAMIC INTELLIGENT SPEED ADAPTATION SYSTEM: A PRELIMINARY ANALYSIS

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ABSTRACT
Intelligent speed adaptation (ISA) has been shown to be an effective measure for road safety improvement. Recently, there has been an increasing interest in using ISA systems, particularly with the dynamic speed control, to manage congestion and reduce energy/emissions. The effectiveness of the dynamic ISA system relies on its speed control strategies. This paper presents the development of a preliminary method to determine control speeds of the dynamic ISA system. The initial results show reasonable control speeds under various levels of freeway congestion as categorized by freeway level of service.

1 INTRODUCTION
In efforts to decrease speed-related accidents and fatalities on roads, several advanced speed management techniques have been investigated. These techniques include both in-vehicle control (e.g. Almquist et al., 1991; Varhelyi and Makinen, 2001) and external vehicle control (e.g. Carsten and Fowkes, 2000). In the past decade, there has been an increasing interest in speed management techniques that take advantage of intelligent transportation system (ITS) technology. One such technique is *Intelligent Speed Adaptation* or ISA, which uses time and/or location information to manage vehicle speed. More specifically, ISA comprises a process that monitors the current speed of a vehicle, compares it to an externally defined set speed, and takes corrective action (e.g., advising the driver and/or governing the top speed). There are many forms of ISA, most of them relying on modern technology such as Global Position System (GPS) receivers, on-board roadway databases, and/or wireless communication. ISA can be implemented in many ways, depending on how the set speed is determined:

1. *Fixed:* in this case, the maximum permissible speed is set by the user and the on-board control system never exceeds that value; for this, ISA can be implemented as an independent on-board control system.
2. *Variable:* in this case, the set speed is determined by vehicle location, where different speed limits are set spatially. This is the most common implementation of ISA, where the maximum vehicle speed never exceeds the speed limit for a given area. This can be implemented based solely on position information or based on broadcasted values.
3. *Dynamic:* in this case, speed is determined by time and location. The temporal aspect can vary based on road network conditions or weather. This information can be provided from a transportation management center via vehicle-infrastructure communication.

Another dimension to ISA systems is how it intervenes with driver behavior. Categories include:

1. *advisory*, where limits are displayed on a messaging device and the driver changes vehicle speed accordingly;
2. *active support*, where the control system can change vehicle speed but driver can override; and
3. *mandatory*, where ISA controls maximum speed and driver cannot override.

Field trials of ISA have taken place over the last several years in many European countries, for example, Sweden (Biding and Lind, 2002), Netherlands (Vanderschuren et al., 1998), and Belgium (Page, 2004). Although the results of the field trials vary from one country to another (e.g. accident rate reduction in the range of 10-49%), there is a consensus that ISA can be used as an effective measure for road safety improvement. Some other ISA studies also show that ISA can improve traffic flow as well as reduce fuel consumption and emissions.

1.1 Dynamic ISA System

Most of the ISA field trials have focused on the variable speed control where a driver is advised or enforced to drive at speeds not above the speed limit for a given road segment. With the availability of real-time traffic information, the field implementation of the dynamic speed control is possible that can also provide mobility and energy/environment benefits when roadways are congested. The preliminary experiment carried out in the United States (U.S.) using the dynamic ISA system showed premise in reducing fuel consumption (13%) and emissions (12-48%) from the vehicle although the travel time increased by 6% (Servin et al., 2006). This type of speed control strategies can dynamically change in relation to current traffic conditions. In this system, several different components interact together. The architecture of the system takes advantage of the existing Freeway Performance Measurement System (PeMS), developed by the University of California at Berkeley and California Department of Transportation (Choe et al., 2002). The PeMS system consists of numerous embedded loop detectors on the major freeways in California, each which reports flow and occupancy from which speed can be computed. These data are collected through local Traffic Management Centers, and then filtered, processed, and made accessible at 30-second intervals on the Internet via the PeMS server. Depending on the speed control strategy, PeMS data (e.g., average traffic speed on a link-by-link basis) can be acquired, processed, and communicated to ISA-equipped vehicles via a wireless communications provider.

There are several ways in which dynamic speed control strategies can be developed. For instance, Oh and Oh (2005) developed a control strategy based on an analytical derivation of a macroscopic traffic flow model. They also proved the effectiveness of their control strategy using a macroscopic simulation tool. In this case, the derivation of the control strategy is based on the traffic flow characteristics of the overall traffic stream. In the context of ISA, it is equivalent to the assumption that every vehicle is equipped with an ISA system (i.e. 100% penetration rate).

1.2 Effect of ISA penetration rate

It is reasonable to think that a 100% ISA penetration rate would be very difficult to achieve in the near term. Doing so will require an enormous amount of investment in both vehicles and infrastructures as well as a strong support from policies and regulations. For early deployment in the U.S., the dynamic ISA is likely to gain more public acceptance if it is to be regard as one of the features in the assisted driving technology. Currently, there are already commercial navigation systems that are capable of functioning like a variable ISA. These navigation systems can display the speed limit of the road on which a vehicle is traveling and warn the driver if the vehicle is traveling at speeds faster than the speed limit. In addition, many of these navigation systems can receive and utilize real-time traffic information in their routing decisions. With all these capabilities, the dynamic ISA system may simply be developed as an extension of these navigation systems.

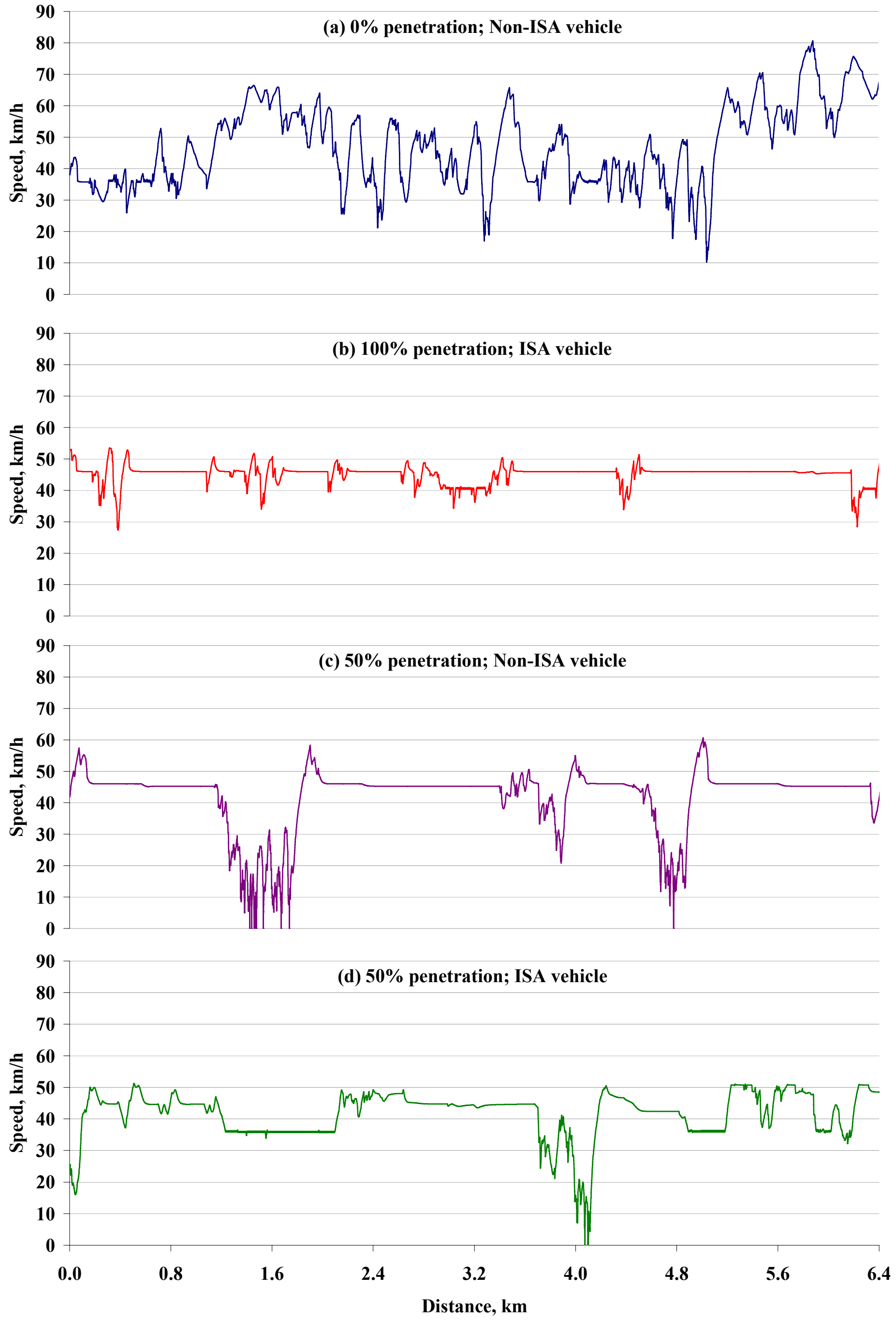


Figure1: Effect of ISA penetration rates on vehicle speed trajectory.

Since not every vehicle on the roads will essentially have the dynamic ISA system, it is necessary to evaluate its impact under varying market penetration rates. Figure1 shows simulated second-by-second speed trajectories of a vehicle driving on an arbitrary basic freeway segment under three different ISA penetration rates: 1) 0%, 2) 100%, and 3) 50%. In Figure 1(a), it can be seen that under congested freeway condition the vehicle travels across a wide range of speed (30-60 km/h). The driving trajectory shows very frequent speed changes due to unstable traffic flow. Overall, the average travel speed of this driving trajectory is approximately 45 km/h. Any portion of the trajectory that is below 45 km/h will result in a travel time penalty. On the other hand, any portion of the driving that is above 45 km/h will provide travel time saving. Ideally, a vehicle traveling at a constant speed of 45 km/h across the same freeway segment will spend the same amount of travel time but much less energy. In addition, the smoother driving trajectory can reasonably be expected to be safer. An example of such driving trajectory is shown in Figure 1(b) for the case of 100% penetration. It can be seen that the speed trajectory is mostly at 45 km/h although there are some speed fluctuations. These speed fluctuations are a result of random vehicle-to-vehicle interactions on the road. In the case of 50% penetration in Figures 1(c) and 1(d), not only the ISA vehicle but also the non-ISA vehicles have smoother driving trajectories. This is because the non-ISA vehicle is hold up by the surrounding traffic, which is made of some ISA vehicles.

1.3 Objectives

The main objective of this study is to develop speed control strategies for a dynamic ISA system. For these strategies to be effective and practical, they need to take into account several considerations from every aspect of vehicle, driver, infrastructure, and environment. Examples of these considerations may include:

- What will be the source of traffic data? What types of traffic data are available from these sources?
- In addition to average traffic speed, what other traffic parameters should be used in the calculation of the control speed? How the different levels of congestion should be factored in the calculation?
- If using the advisory system, how far in advance should the driver be advised of the control speed? How often should the control speed be updated (e.g. every kilometer or every five kilometers) that will not distract the driver?
- If using the active support or mandatory system, how abrupt should the control speed be changed that will not cause adverse impacts on safety? Again, how often should the control speed be updated that will not cause discomfort to the driver?

This paper focuses on the development of methods to determine control speeds of the dynamic ISA system under various levels of freeway congestion. The goal of these methods is to achieve energy/emissions reduction while eliminating or minimizing the travel time penalty. A preliminary method is presented along with some initial results.

2 METHODOLOGY

Under congested conditions, it is well known that traffic instability (i.e., stop-and-go conditions) can often develop. This instability generally takes place when traffic is flowing at or near the roadway capacity, and some type of perturbation occurs (e.g., sudden slowing, lane drop, accident, etc.). Traffic flow instability is characterized by significant speed variations in the individual vehicles due to the random and non-homogenous nature of individual driver behavior. The traffic congestion on freeways has been categorized into different "levels-of-service" or LOS based on the density of traffic (TRB, 2000). There are six LOS values that range from the letters "A – F". For these different levels of service, a typical speed trajectory of a vehicle will have different characteristics. Under LOS A, vehicles will typically travel near the highway's free flow speed, with little acceleration/deceleration perturbations. As LOS conditions get progressively worse (i.e., LOS B, C, D, E, and F), vehicles will encounter lower average speeds with a greater number of acceleration/deceleration events.

2.1 Control speed determination

We adopt the freeway LOS as another traffic parameter in the calculation of the dynamic control speeds. For each LOS, the control speed can be calculated as an average traffic speed plus a certain amount of speed adjustment. This speed adjustment is aimed at compensating high speed peaks that are eliminated as a result of the speed control mechanism. Given that the amount of speed adjustment is a function of the standard deviation of traffic speed trajectories, the control speed for traffic under LOS *i* can be written as:

$$v_i^c = \overline{v}_i + k_i \cdot s_i \qquad (1)$$

where:
v_i^c = control speed (km/h)
$\overline{v}_i$ = mean of second-by-second traffic speed (km/h)
k_i = constant
s_i = standard deviation of second-by-second traffic speed (km/h)
i = {LOS A, LOS B, LOS C, LOS D, LOS E, LOS F}

The aggregated traffic speed collected by PeMS can be used to represent the mean of second-by-second traffic speed. However, the data regarding the standard deviation of second-by-second traffic speed is not readily available. This data was derived from driving trajectory data collected for each LOS. The next step is to determine an optimal *k* value for each LOS. This is done through the use of microsimulation, which will be described in the following sections.

2.2 Traffic data collection

Driving trajectory data were collected by probe vehicles on freeways in Southern California during September 2005, May 2006 and March 2007. To represent general traffic conditions, the data collection activities occurred uniformly over the daytime. The data collection dates was also equally distributed from Monday to Friday. We used multiple drivers in order to take into account the fact that different people drive differently even under the same freeway LOS.

In addition to the probe vehicle data, macroscopic traffic data (i.e. LOS) from PeMS were gathered. Using information about latitude, longitude, and time stamp, probe vehicle data were spatially and temporally matched with the PeMS data. Typically, vehicle detector stations (VDS) in the PeMS network are located around 0.6-1.0 miles apart from each other. The spatial coverage of each VDS is from the mid point between itself and the VDS to its left to the mid point between itself and the VDS to its right. LOS for each loop detector at each VDS is updated every 30 seconds. Therefore, for every 30-second period the second-by-second driving trajectories were spatially mapped with the corresponding VDS. A vehicle running in lane *l* within the coverage of VDS *i* at time *t* is considered to experience the LOS reported by the loop detector in lane *l* at VDS *i* during period *p*. Note that the lane information was simultaneously collected by the driver when the probe vehicle runs were taken place. The LOS of the lane the driving trajectory is in was then assigned to each second of driving data. This process started at the beginning of the driving trace and was repeated until the end of the driving trace was reached.

Table 1 summarizes the statistics of the second-by-second speed data for each LOS. Figure 2 plots the mean speed and its variation for each LOS. It can be seen that the mean speed values correlate well with the definition of each LOS. LOS A, B, and C are in stable flow. Thus the mean speed values are relatively high and the speed variations are low. The mean speed values for LOS D, E, and F drops significantly from one LOS to the next LOS. The speed variation is highest for LOS D and E.

Table1: Statistics of measured second-by-second speeds.

LOS	N (seconds)	Max (km/h)	Min (km/h)	Mean (km/h)	Standard Deviation (km/h)	95% Confidence Level	Coefficient of Variation
A	1721	137.7	94.8	121.7	7.0	0.3	0.1
B	1892	138.7	69.0	114.0	11.5	0.5	0.1
C	2414	130.3	69.0	108.2	10.8	0.4	0.1
D	1770	133.5	6.1	89.8	27.5	1.3	0.3
E	1104	127.3	0.0	58.6	35.2	2.1	0.6
F	6195	97.8	0.0	23.8	17.1	0.4	0.7

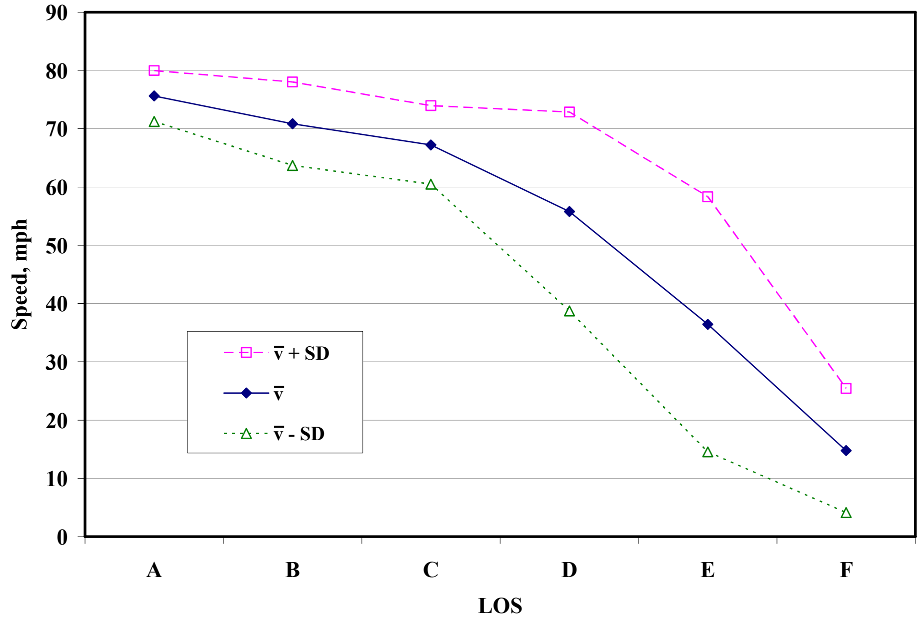


Figure2: Variation of speed trajectories under different levels of congestion.

2.3 Simulation setup

Using PARAMICS microsimulation software (Quadstone, 2006), a basic freeway segment is coded as shown in Figure 3. For this freeway segment, different levels of congestion are induced by varying the travel demand on the segment. Various control speeds are set on ISA vehicles in the simulation that represent different *k* values. The simulation is run and the speed trajectories of both ISA and non-ISA vehicles are traced. Then, these speed trajectories are used to calculate travel time and estimate energy/emissions using the Comprehensive Modal Emissions Model (Barth et al., 1999). Due to the stochastic nature of microsimulation, for each scenario (i.e. each *k* value) the ISA and non-ISA vehicles are traced multiple times to obtain multiple travel time and energy/emissions data. This is to ensure that the mean values of these data will be statistically significant.

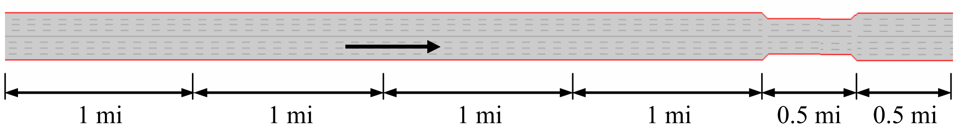


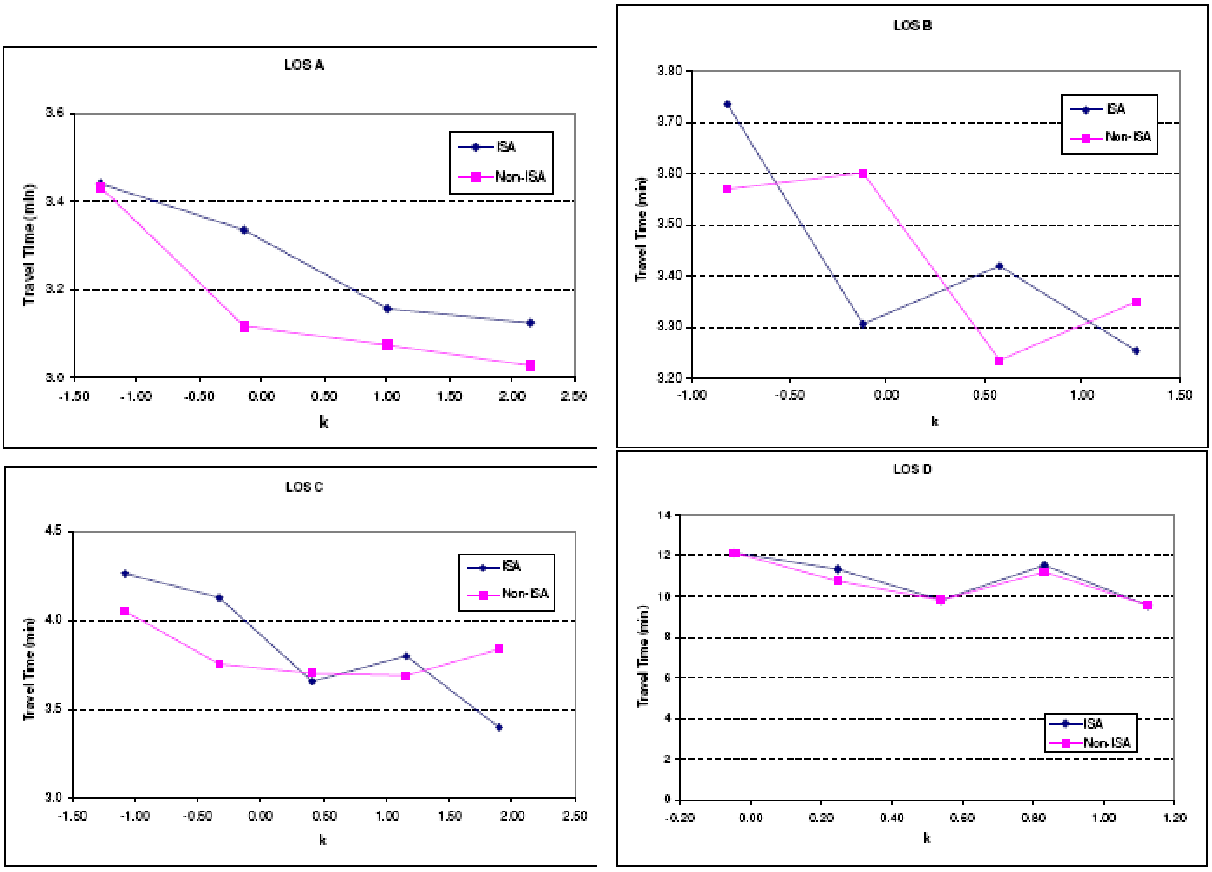
Figure3: Basic freeway segment used for simulation.

3 RESULTS

This paper presents the results only for the ISA penetration rate of 20%. It was shown earlier that this amount of ISA penetration was enough to provide significant energy and emissions benefits (Servin et al., 2006).

3.1 Control speed versus travel time

The plots of control speed versus mean travel time for each LOS are shown in Figure 4. The larger the value of *k*, the higher the control speed. According to the figure, the general trend is that the higher the control speed, the lesser the travel time. This is quite true although there are some exceptions, especially in LOS E. Using this figure, the optimal *k* value with regards to eliminating/minimizing travel time penalty for each LOS can be identified.



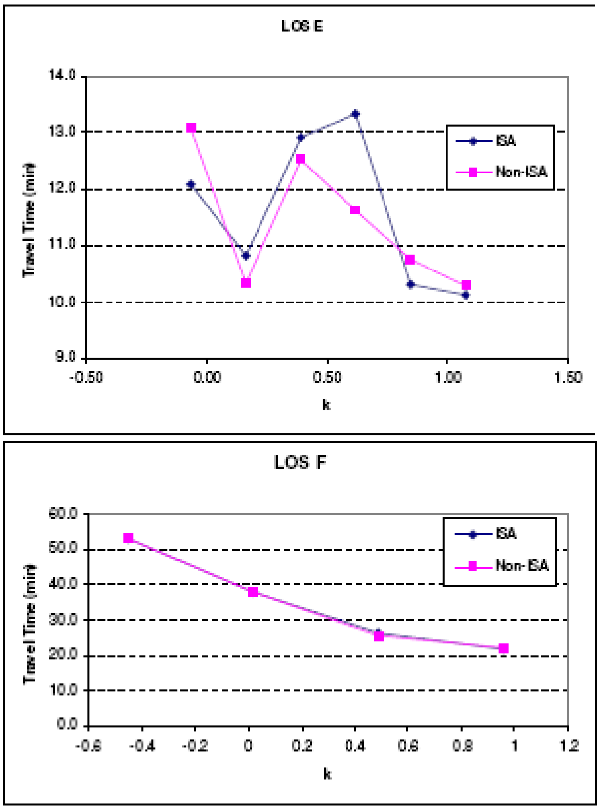
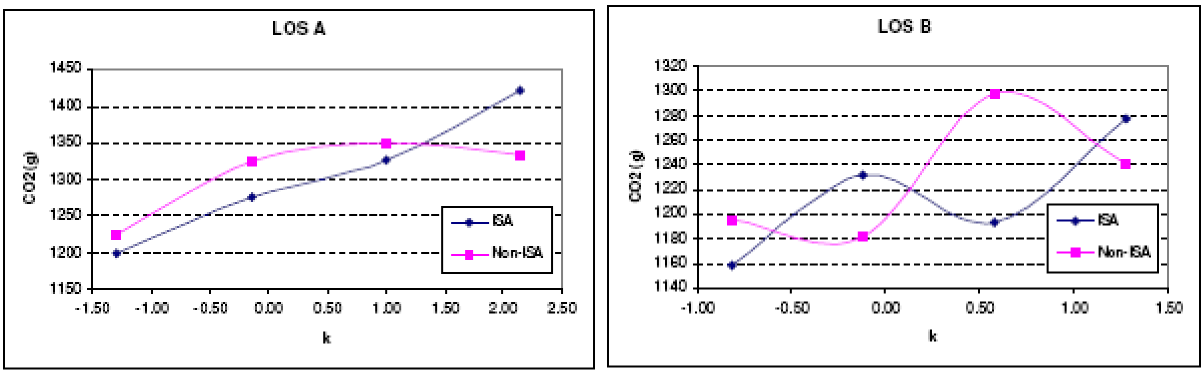


Figure4: Effect of control speeds on travel time under different levels of congestion.

3.2 Control speed versus energy/emissions

The plots of control speed versus the mean values of estimated carbon dioxide (CO_2) emission for each LOS are shown in Figure 5. Only CO_2 is shown for brevity. According to the figure, the general trend is that the higher the control speed, the more the CO_2 emission. This is quite true although there are some exceptions, especially in LOS D and F. Using this figure, the optimal *k* value with regards to minimizing CO_2 emission for each LOS can be identified.



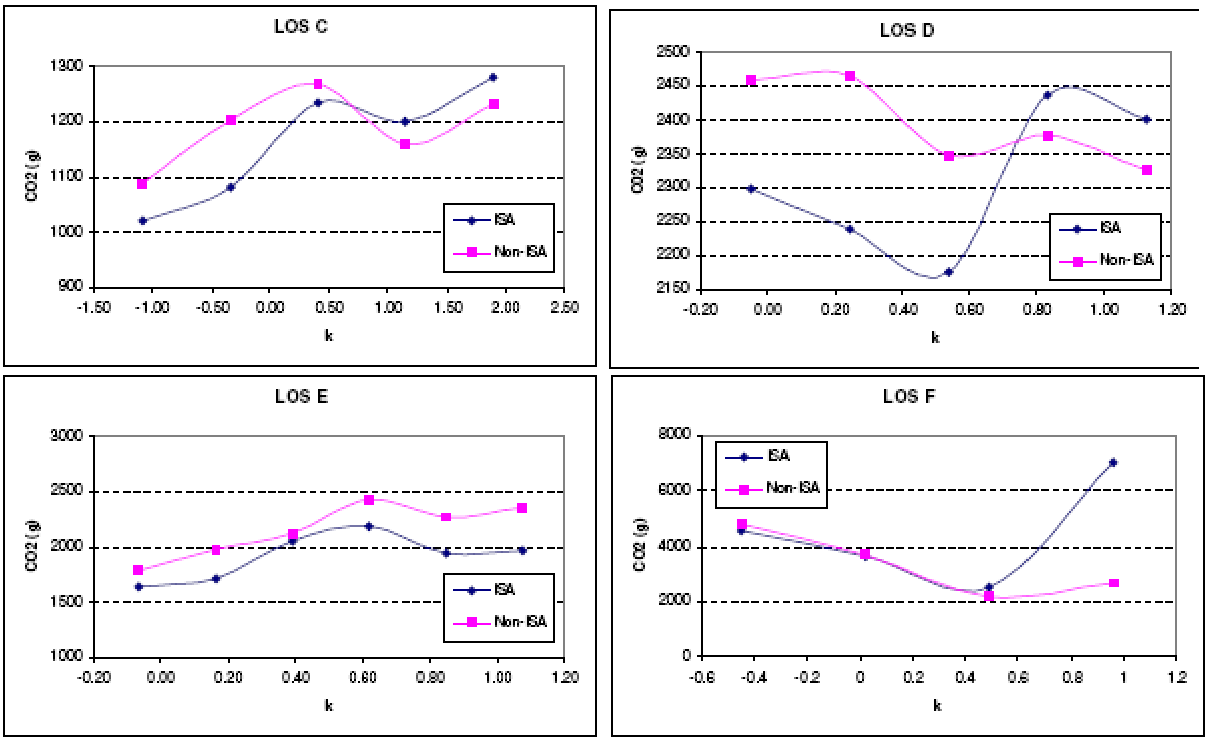


Figure5: Effect of control speeds on CO_2 under different levels of congestion.

3.3 Discussions

The selection of the control speeds based on two different objectives may not result in the same speed value. Therefore, both objectives have to be considered together. In this paper, a priority is given to the objective of eliminating/minimizing the travel time penalty. The selected *k* value for each LOS is given in Table 2. They are also discussed below:

- *LOS A*: Figure 4 shows that the travel time penalty can not be eliminated. It can only be minimized by choosing high control speeds. However, as the original intention of ISA is to improve road safety by controlling speeding, it is necessary to set a cap of the control speed. In this case, the speed of 120 km/h is chosen as a cap speed. Thus, the appropriate *k* value for this LOS is found to be 0.
- *LOS B*: The optimal *k* value is in the range of 0.15-0.30. Given that the travel time objective has higher priority, the *k* value is chosen to be 0.15.
- *LOS C*: For this LOS, it is quite obvious that the optimal *k* value is 0.35.
- *LOS D*: It is also obvious that the optimal *k* value for this LOS is 0.55.
- *LOS E*: Two values of *k* result in the same amount of travel time. However, *k* equal to 0.1 causes less amount of CO_2 and thus is chosen.
- *LOS F*: Because the traffic is already very congested, there is not much travel time difference between ISA and non-ISA vehicles. The higher the control speed, the less the travel time for both types of vehicles. However, the CO_2 emission increases dramatically when *k* is greater than 0.45.

Table2: Selected *k* values and corresponding control speeds.

LOS	Selected *k*	$\bar{v}$ (km/h)	*s* (km/h)	Computed v^c (km/h)	Final v^c (km/h)
A	0.00	121.7	7.0	121.7	120
B	0.15	114.0	11.5	115.7	115
C	0.35	108.2	10.8	112.0	110

D	0.55	89.8	27.5	104.9	105
E	0.10	58.6	35.2	62.1	65
F	0.45	23.8	17.1	31.5	30

Also shown in Table 2 are the computed and final control speeds. The mean speed values from Table 1 are used as example to compute the control speeds. Then, the computed control speeds are rounded to the nearest speed with an increment of 5 km/h to obtain the final control speeds.

4 CONCLUSIONS AND FUTURE WORK

This paper presents the development of a preliminary method to determine control speeds of the dynamic ISA system under various levels of freeway congestion. The method is based on finding an optimal speed adjustment to compensate high speed peaks that are eliminated as a result of the speed control mechanism. The initial results show reasonable control speeds under different levels of congestion as categorized by LOS.

In the future, the developed methodology will be tested in as a simulation of an actual freeway network that will be calibrated to the real-world traffic data. Improvement and refinement will be made to the methodology to achieve better and more comprehensive dynamic speed management strategies. The development of such dynamic speed management strategies will be useful to the advancement of the assisted driving technology in the future.

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