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DYNAMIC SPEED CONTROL STRATEGY FOR FREEWAY TRAFFIC CONGESTION MANAGEMENT

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Abstract: This study investigates the effects of speed control on traffic flow processes and develops a control strategy to maximize the efficiency of freeway systems. The basic idea of the speed control is to advise or force drivers to decelerate gradually in order to cope with such operational problems on a freeway or highway as incidents, construction, or geometric changes, etc. Theoretical derivation of optimal speed control scheme for multiple freeway sections is presented based on a macroscopic traffic flow process model. Simulation experiments demonstrate the effectiveness of the derived speed control scheme and provide a promising potential for field implementation. These results indicate that the temporal spatial speed limitation helps in maintaining stable freeway traffic conditions.

Key Words: Speed Control, Traffic Flow, Optimal Control, Traffic Simulation

1. INTRODUCTION

In order to improve performance of freeway systems, many control schemes have been studied and implemented. These efforts can be divided into three categories: ramp metering, route guidance, and speed control. Although there have been many investigations of ramp metering and route guidance systems as freeway traffic management strategies, relatively less attention has been given to speed control strategies, particularly in U.S. applications. Speed limits generally have been regarded as a fixed influence on traffic safety. That is, speed limits have been studied within the context of safety enhancement, rather than as a means of freeway traffic management. However, by coupling recent advances in freeway traffic monitoring systems, it is now possible to manage mainline traffic via speed limits that vary dynamically dependent on traffic conditions. In contrast to ramp metering that regulates traffic entering to freeway, speed control strategies can offer a direct and effective way of controlling mainline traffic.

Speed control can be implemented either via variable speed signs or through advanced communication devices between vehicles and roadside beacons. More advanced systems, Intelligent Speed Adaptation (ISA) systems, are being introduced that are capable of enforcing the speed limit directly to the vehicles. Although the in-car speed limiter appeared utopist when the concept was first proposed (Almqvist *et al.*, 1991), recent automatic speed limiting by the in-car speed limiter has been shown to be very promising (Hogema and Horst,1999) and field trials in European countries have been carried out (Várhelyi and Mäkinen, 2001). Effective implementation of speed control is becoming plausible. However, finding the time-varying optimal speeds is not a trivial task, and yet to be studied in detail.

The main focus of this paper is to find the theoretical optimal speeds for a stretch of freeway comprised of multiple sections. This study incorporates a fundamental traffic flow model to investigate the relationship between the system performance and the desirable speeds along freeway sections under disruptive traffic condition due to a bottleneck induced by any of various reasons, including an incident, construction, or geometric inconsistency, etc.

In the literature, there have been several studies on speed control systems for freeway traffic management since Zacker (1972) first reported some experiments of variable speed limits and Cremer (1976) established a combined control strategy for ramp metering and speed control using nonlinear programming and short-term prediction. While Cremer and Schoof (1989) proposed a coordinated and traffic responsive control strategy for urban traffic corridors, including ramp metering, speed control, route diversion, and signal control on surface streets, Smulders (1990) proposed a hysteresis type control strategy that optimizes the throughput of the freeway section using homogenizing control (Toorenburg, 1983). In a different approach, Kühne (1991) proposed a speed control algorithm in which the standard deviation of speed distribution is regarded as one of the decision variables to determine speed limit criteria. Várhelyi (1996) proposed a system for dynamic speed adaptation in adverse driving conditions, and Alessandri *et al.* (1999) applied Powell's method to solve the nonlinear optimization problem for freeway control using variable speed signaling.

Although there have been several significant research studies on speed control strategy for traffic management, most works have focused on solving a non-linear optimization problem based on the empirical investigation of changes in the traffic flow model relationship by speed limitations (Cremer, 1976; Smulders, 1990). Unlike previous studies on speed control, the current study avoids complicated stochastic traffic flow modeling process in seeking the optimal speed control scheme. Rather, this study employs a simple fundamental traffic flow model process (Lighthill and Whitham, 1955; Richard, 1956), so called LWR model, to investigate the relationship between speed control and traffic characteristics. This study develops a multi-section coordinated speed control strategy that maximizes throughput from the congested section. State equations for desirable speeds are derived from the traffic flow relationship.

The outline of this paper is as follows. The next section identifies the speed control problem in detail. The optimal speed control scheme is presented in the third section using macroscopic relationships among traffic parameters. The fourth section demonstrates capability of speed control in managing freeway traffic congestion by means of macroscopic traffic simulation. The final section concludes this paper with the discussion on future research directions in speed control for freeway traffic management.

2. PROBLEM IDENTIFICATION

The causes of freeway traffic congestion are many. As identified in a number of studies (Edie, L.C. and Foote, 1960; Koshi et al., 1992; Del Castillo, 2001), traffic congestion is a symptom resulting from the instability of traffic flow. Usually, the instability occurs under conditions near capacity of the freeway section whereby a small perturbation in traffic flow easily creates propagation of shock waves that, in such traffic conditions, often lead not only to traffic congestion but also to traffic accidents. That is, freeway congestion can be explained by speed variations due to the random and non-homogenous nature of driver behavior and the

instability of the traffic condition.

Considering these two reasons for the traffic congestion, controlling vehicles' speeds in a section can be a powerful tool in that the control can reduce both speed variations as well as the quantity of traffic flow movement. While speed variations can be dealt with at an individual vehicle level via Adaptive Cruise Control (ACC) or Intelligent Speed Adaptation (ISA), the instability of traffic conditions can best be dealt with at a macroscopic control level. This study focuses on a macroscopic-level optimal speed control to improve the efficiency of the freeway system under conditions in which traffic congestion occurs due to an operational or physical bottleneck.

In order to alleviate such a congested traffic condition, a dynamic speed control strategy can be applied. Reduction of travel speed upstream leads to less congestion at the bottleneck, which may improve overall performance of the freeway system. In fact, the objective of traffic management can be formulated as a throughput maximization problem. When a bottleneck is identified on a stretch of freeway, maximizing throughput at the bottleneck would be the best for the overall system performance. In a simple stretch of freeway with a bottleneck at section *i* as in Figure 1, the optimal solution can be achieved when maximizing the throughput (q_i) at section *i*. To achieve the maximum throughput at section i, a series of speed control strategies at the upstream stations may need to be coordinated.

This study seeks the optimal speeds at upstream stations to maximize the throughput on a stretch of freeway with multiple sections. The purpose of the paper is not to find achievable optimal speeds with consideration of driver compliance, but to find theoretical target optimal speeds for each section. The target speeds can be achieved via advisory variable speed limits, mandatory speed limits, or in-car speed limiters. Of course, for implementation, the optimal speeds need to be updated by employing a feedback control system (Papageorgiou, 1983).

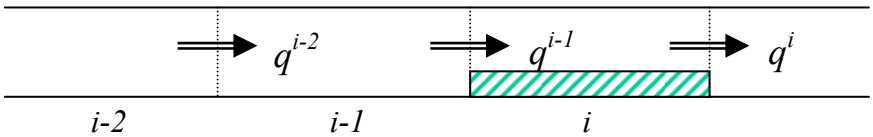


Figure 1. Freeway Bottleneck

3. MODEL DEVELOPMENT

There are various mathematical models representing traffic process that can be employed in the development of traffic control strategy. This study employs a simple fundamental traffic flow model process to investigate the relationship between speed control and traffic characteristics, avoiding complicated stochastic traffic flow modeling process. A multi-section coordinated speed control strategy is derived from the macroscopic relationship that maximizes throughput in the congested section.

3.1 Freeway Traffic Flow Model

This study assumes the traffic flow process on freeway to be governed by the macroscopic LWR model. LWR model is based on a continuum representation of traffic and is equivalent to the fluid conservation equation that characterizes compressible flow, that is,

$$\frac{\partial q}{\partial \mathrm{x}} + \frac{\partial \mathrm{k}}{\partial \mathrm{t}} = g(x,t) \tag{1}$$

where,
q = flow rate (vehicles/hour)
k = density (vehicles/mile)
g = net vehicle generation rate (vehicles/hour/mile)
x = location (space)
t = time

In conventional macroscopic models, the fluid conservation equation is usually coupled with the identity, $q = u\,k$ (where u is travel speed), and a speed-density relationship. Speed, u, is described by the relationship between speed and traffic density under equilibrium condition, i.e., $u = u_e(k)$. The model is solved numerically using discrete time steps and discretized highway sections. Figure 2 represents a stretch of freeway discretized by sections.

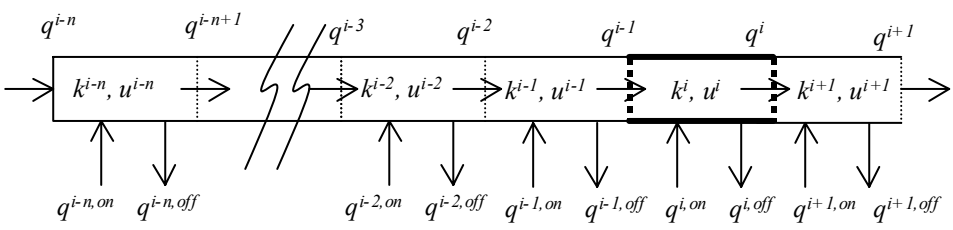


Figure 2 Discritized Freeway Sections

Let us consider $k^i(t)$ as the traffic density in section i at time t, and define l_i as the number of lanes at section i. In addition, let us define $q^i(t)$ as the flow moving from section i to section $i+1$. q_i^{on} and q_i^{off} denote flows entering and exiting out of section i via on and off ramps, and l_{on} and l_{off} represents the number of lanes of on and off ramps, respectively. Then the density equation over discrete time is represented as:

$$k^i(t) = k^i(t-1) + [\frac{\Delta t}{l_i \cdot \Delta x_i}][l_{i-1} \cdot q^{i-1}(t-1) - l_i \cdot q^i(t-1) + (l_{on} \cdot q_{i-1}^{on} - l_{off} \cdot q_{i-1}^{off})] \tag{2}$$

In this study, we use a basic form of Greenshields model (equation 3) to explain the relationship between speed and density. u_f represents the free flow speed and k_j denotes the jam density; then the equilibrium speed is expressed by:

$$u_e^i(t) = u_f \cdot (1 - \frac{k^i(t)}{k_j^i(t)})^\alpha \tag{3}$$

In the model, the speed control parameter is denoted as β, which affects the speed of the section. The optimal speed is determined by multiplying the equilibrium speed by the control parameter.

$$u^i(t) = \beta^i(t) \cdot u_e^i(t) \tag{4}$$

Traffic flow exiting section i is obtained by multiplication of speed and density.

$$q^i(t) = u^i(t) \cdot k^i(t) = \beta^i(t) \cdot u_e^i(t) \cdot k^i(t) \tag{5}$$

3.2 Development of Optimal Speed Control Scheme

In order to simplify the model derivation, only a basic freeway section (i.e., no on and off ramps) is assumed. We also assume that the optimal speed cannot be higher than the free flow speed, which means that the speed control strategy is to limit the maximum speed.

Derivation of optimal speed for the first upstream section

As stated previously, for the simplicity of the formulation, it is assumed that there is no on or off ramp involved and that the parameter α in Greenshields speed-density model is equal to 1.0. Also Δt, Δx, and l are omitted by assuming Δt = 1 minute, Δx = 1 mile, and l = 1 lane without loss of generality. Let us assume that traffic congestion has occurred due to some reason (incident, construction, or geometric inconsistency) at section i in Figure 2. The section i can be regarded as a bottleneck.

First, the objective of the speed control is formalized as a throughput maximization problem. From the basic macroscopic relationship, the theoretical maximum flow rate at the bottleneck i can be easily found as equation (7). That is, the throughput is maximized when density of the section is kept a half of the jam density.

$$q^i(t) = u^i(t) \cdot k^i(t) \tag{6-1}$$

$$= u_f^i (1 - \frac{k^i(t)}{k_j^i}) \cdot k^i(t) \tag{6-2}$$

$$\max q^i(t) = \frac{1}{4} u_f k_j(t) \Big|_{k=\frac{1}{2}k_j} \tag{7}$$

Next we consider inflow from the upstream section, i-1, to the bottleneck, i, to maintain the optimal density level ($\frac{1}{2}k_j$) that allows maximum through at section i. Then the density at section i at time t can be expressed as equation (8-1) and the inflow from section i-1 at time t can be expressed as equation (8-2).

$$k^i(t) = k^i(t-1) + q^{i-1}(t-1) - q^i(t-1) = \frac{1}{2}k_j^i \tag{8-1}$$

$$q^{i-1}(t-1) = \frac{1}{2}k_j^i + q^i(t-1) - k^i(t-1) \tag{8-2}$$

Meanwhile, the flow entering to section i can also be expressed as a function of traffic condition on section i-1 as equation (9-1), and the equation can be written as equation (9-2) by adding the speed control parameter $\beta^i(t-1)$.

$$q^{i-1}(t-1) = u^{i-1}(t-1)\cdot k^{i-1}(t-1) \tag{9-1}$$

$$= \beta^{i-1}(t-1)\cdot u_e^{i-1}(t-1)\cdot k^{i-1}(t-1) \tag{9-2}$$

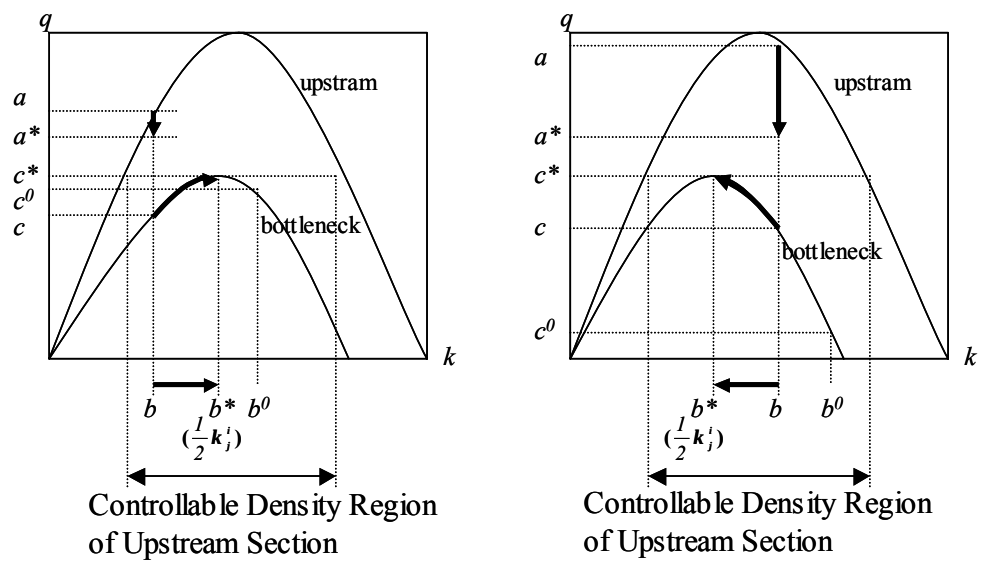
Since both equation (8-2) and (9-2) represent inflow from section i-1, the optimal speed parameter can be derived as:

$$\beta^{i-1}(t\text{-}1) = \frac{\frac{1}{2}k_j^i + q^i(t-1) - k^i(t-1)}{u_e^{i-1}(t-1)\cdot k^{i-1}(t-1)} \tag{10-1}$$

or

$$= \frac{\frac{1}{2}k_j^i + q^i(t-1) - k^i(t-1)}{u_f(1-\frac{k^{i-1}(t-1)}{k_j^{i-1}})\cdot k^{i-1}(t-1)} \tag{10-2}$$

The optimal speed control parameter β ranges from 0 to 1, implying that practically the optimal speed cannot exceed the free flow speed. This speed control can be graphically explained depending on current traffic conditions as shown in Figure 3. The speed control strategy is shown to be an effective control method in that throughput at the bottleneck is maximized.



(a) Light Traffic with Bottleneck (b) Heavy Traffic with bottleneck

Figure 3. Speed Control for Throughput Maximization

Without speed control, the density at the bottleneck increases (b → b^0) and the maximum optimal throughput cannot be achieved (c^0). However, as inflow decreases (a → a^*) by means of speed control at upstream section, the density at the bottleneck decreases (b → b^*) so as to maximize throughput at the bottleneck (c → c^*).

Derivation of speed control for the upstream sections

The next problem is to manage the further upstream sections. A similar control concept is applied, but two additional constraints are added: (1) maintenance of controllable density level and (2) maximization of number of vehicles in the section to minimize propagation of congestion to upstream sections. The first constraint implies that this section should be able to move more vehicles than the bottleneck section's maximum throughput, so that the bottleneck section can maintain maximum throughput. Only when the density level of the section i-1 is within the controllable range, the inflow to section *i* can be controlled by means of speed control. If the density is out of the range, less traffic moves to the bottleneck section, which results in inefficiency of the system. Considering both constraints, the optimal density at section i-1 is the upper limit of the controllable region.
The optimal speed control for the further upstream section i-2 can be derived from the relation with the level of density at section i-1. First, the controllable density region of the upstream section i-1 can be expressed by $q^i_{\max} \le q^{i-1}(t-1)$ as the constraint (1). If maximum flow rate at the bottleneck section i, $q^i_{\max}$, is greater than inflow, $q^{i-1}(t-1)$, we do not need to operate the speed control since the density of the bottleneck section still stays at lower level than the desirable density ($\frac{1}{2}k^i_j$). The controllable density region can be derived from the constraint, $q^i_{\max} \le q^{i-1}(t-1)$ as follows:

$$q^i_{\max} \le q^{i-1}(t-1) \tag{11-1}$$

$$\frac{1}{4}u^i_f \cdot k^i_{ji} \le u^{i-1}(t-1) \cdot k^{i-1}(t-1) \tag{11-2}$$

$$\frac{1}{4}u^i_f \cdot k^i_j \le u^{i-1}_f \cdot (1-\frac{k^{i-1}(t-1)}{k^{i-1}_j}) \cdot k^{i-1}(t-1) \tag{11-3}$$

$$\frac{k^{i-1}_j}{2}\left(1-\sqrt{1-\frac{k^i_j \cdot u^i_f}{k^{i-1}_j \cdot u^{i-1}_f}}\right) \le k^{i-1}(t-1) \le \frac{k^{i-1}_j}{2}\left(1+\sqrt{1-\frac{k^i_j \cdot u^i_f}{k^{i-1}_j \cdot u^{i-1}_f}}\right) \tag{11-4}$$

The optimal density at section i-1 can be expressed by the upper limit of the controllable region (12-1) to satisfy the constraint (2) or by the relationship between inflow and outflow (12-2).

$$k^{i-1}(t-1) = \frac{k^{i-1}_j}{2}\left(1+\sqrt{1-\frac{k^i_j \cdot u^i_f}{k^{i-1}_j \cdot u^{i-1}_f}}\right) \tag{12-1}$$

$$k^{i-1}(t-1) = k^{i-1}(t-2) + q^{i-2}(t-2) - q^{i-1}(t-2) \tag{12-2}$$

$$q^{i-2}(t-2) = \frac{k^{i-1}_j}{2}\left(1+\sqrt{1-\frac{k^i_j \cdot u^i_f}{k^{i-1}_j \cdot u^{i-1}_f}}\right) + q^{i-1}(t-2) - k^{i-1}(t-2) \tag{12-3}$$

Then, we can obtain speed control parameter β for the section i-2 from equations of (9-2) and (12-3).

$$\beta^{i-2}(t-2) = \frac{q^{i-2}(t-2)}{u_f^{i-2}(1-\frac{k^{i-2}(t-2)}{k_j^{i-2}}) \cdot k^{i-2}(t-2)} \tag{13-1}$$

or

$$= \frac{\frac{k_j^{i-1}}{2}(1+\sqrt{1-\frac{k_j^i \cdot u_f^i}{k_j^{i-1} \cdot u_f^{i-1}}}) + q^{i-1}(t-2) - k^{i-1}(t-2)}{u_f^{i-2}(1-\frac{k^{i-2}(t-2)}{k_j^{i-2}}) \cdot k^{i-2}(t-2)}) \tag{13-2}$$

Equation (13-2) can be generalized for the nth upstream section from the bottleneck section at time t-n as follows:

$$\beta^{i-n}(t-n) = \frac{\frac{k_j^{i-n+1}}{2}(1+\sqrt{1-\frac{k_j^i \cdot u_f^i}{k_j^{i-n+1} \cdot u_f^{i-n+1}}}) + q^{i-n+1}(t-n) - k^{i-n+1}(t-n)}{u_f^{i-n}(1-\frac{k^{i-n}(t-n)}{k_j^{i-n}}) \cdot k^{i-n}(t-n)} \tag{14}$$

where, $n \geq 2$

Finally, a set of optimal speeds for a stretch of freeway can be found though equations (10) and (14). These equations are expressed by relating the traffic condition at the downstream section and capacity reduction at the bottleneck section.

4. SIMULATION EXPERIMENT

This section evaluates the effects of speed control strategies via a macroscopic simulation model. The optimal speed for each section is calculated based on the equations derived in previous section. In this simulation, the modified Greenshields model (equation 15) defines speed-density relationship in which minimum speed is included. We assume the model parameter, α, equals to 1, and the minimum speed, u_0, is 5 miles/hr.

$$u^i(t) = (u_f - u_0) \cdot \left(1 - \frac{k^i(t)}{k_j^i(t)}\right)^{\alpha} + u_0 \tag{15}$$

Macroscopic simulation has been performed on a four-lane freeway stretch consisting of eight sections without on and off ramps. Each section is 1-mile in length with a free flow speed of 60 mph, and jam density of the sections is assumed to be 160 vehicle/mile. We assumed an incident blocking a lane at section 7 for 20 minutes. Figure 4 depicts the freeway stretch used for the evaluation of the proposed signal control scheme.

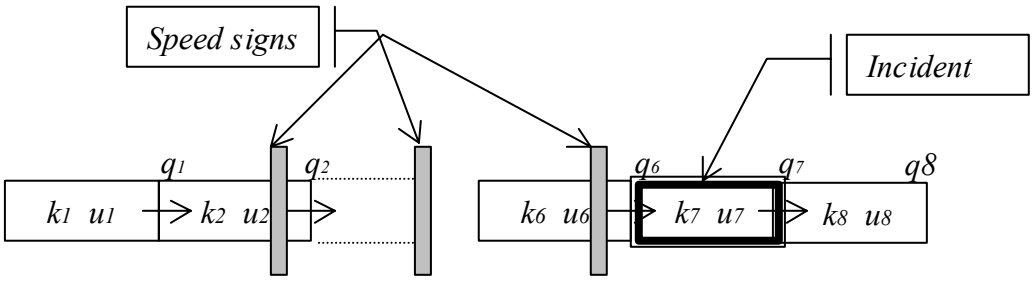


Figure 4. Freeway Stretch for Speed Control Evaluation

The optimal speeds obtained from the equations derived in the previous section are theoretical optimal speeds. The temporal and spatial speed limitations are enforced for drivers to reduce speed gradually via variable speed signs or in-car speed limiters. Extensive simulation experiments were conducted with various demand levels in order to consider all possible traffic conditions.

Figure 5 shows an example of the temporal and spatial changes of speed control parameters in the case for which the volume to capacity (V/C) ratio is 0.75. In this case, time variant speed control should be activated for section 4, 5, and 6 in order to ease the congestion due to the incident: 18 minutes for section 6, 8 minutes for section 5, and 1 minute for section 4.

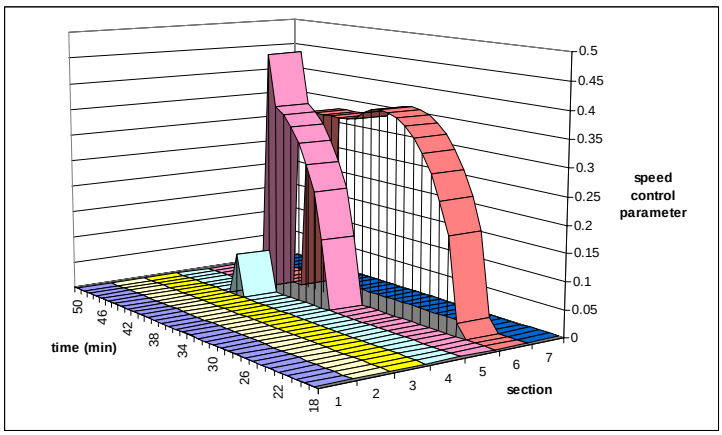
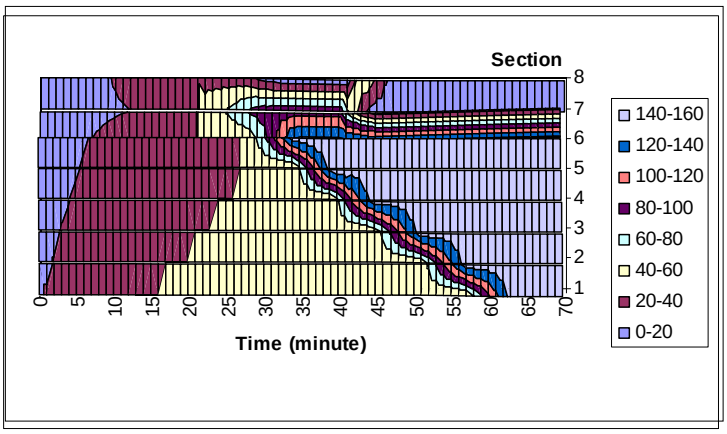
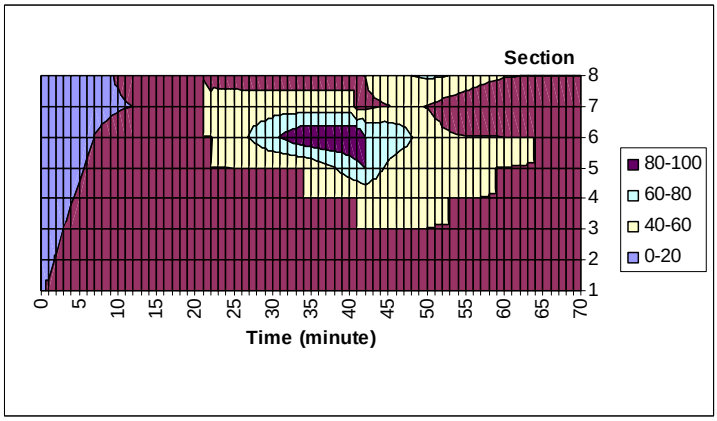


Figure 5 Temporal and spatial speed control parameters (V/C = 0.75)

Figure 6 (a) and (b) show effects of speed control by comparing density profiles between do-not and do case. The shock wave is seen to propagate backward radically and results in severe traffic congestion when there is no control as in Figure 6(a). Alternatively, Figure 6(b) shows a stable traffic condition minimizing shock wave propagation effects.



(a) Density profile (without control)



(b) Density profile (control)

Figure 6. Effects of Speed Control

For the evaluation of the speed control we compare several different performance measures. Temporal Speed Variation (TSV) is designed to evaluate the potential safety enhancement based on the relationship between speed and accident occurrence. Many studies have reported that speed variation is an important parameter leading to an accident occurrence (Solomon, 1964; Cirillo, 1968; Lave, 1985; Tignor, 1989; Harkey, 1990; Oh *et al.*, 2001). Overall performance of the system was measured by throughput, Total Time Spent (TTS), Total Traveled Distance (TTD) and System Average Speed (SAS). The performance measures used in this study are described as follows:

$$TSV = \frac{\sum_{s=1}^{S}\sum_{t=1}^{T-1}\left(\frac{|u_s(t+1)-u_s(t)|}{u_s(t)}\right)}{S \times T} \times 100\,\% \tag{16}$$

$$TTS = \sum_{s=1}^{S}\sum_{t=1}^{T} N_s(t) \times \Delta t \tag{17}$$

$$TTD = \sum_{s=1}^{S}\sum_{t=1}^{T} f_s(t) \times d_s \tag{18}$$

$$SAS = \frac{TTS}{TTD} \tag{19}$$

where
$s = \text{section},$
$S = \text{total \# of sections}$
$t = \text{time step},$
$T = \text{total \# of time steps},$
$\Delta t = \text{length of simulation time step}$
$u = \text{section speed},$
$N = \text{the number of vehicles in the section s during time step t}$
$f = \text{flow, and}$
$d = \text{section length}$

Table 1 summarizes the effects of speed control with different demand levels described by the volume to capacity (V/C) ratio. Overall, the speed control strategy shows excellent performance. For example, when the demand level is 0.75, the speed control scheme increases throughput more than 50%, improves overall speed 90%, and reduces temporal speed variation more than 70%; this latter result implies that the speed control may enhance not only system performance but also safety. Greater benefit is expected in system efficiency as demand increases. Somewhat ironically, this simulation experiment shows that overall speed improves when asking drivers to reduce their speed. It also evidences that the speed control can be an effective and efficient traffic management strategy.

Table 1. Performance Evaluation

Demand (V/C)	Performance measure	No control	Speed control	Improvement (%)
0.7	TSV (%)	3.45	0.97	-71.80
	Throughput (veh)	1106.74	1671.34	51.01
	TTS (min)	30203.70	19720.51	-34.71
	TTD (veh-mile)	13327.67	16593.04	24.50
	SAS(mile/hr)	26.48	50.48	90.68
0.75	TSV (%)	3.61	1.49	-58.76
	Throughput (veh)	1061.96	1780.80	67.69
	TTS (min)	38367.52	22474.23	-41.42
	TTD (veh-mile)	12967.91	17733.6	36.75
	SAS (mile/hr)	20.28	47.34	133.46
0.8	TSV (%)	3.61	3.11	-13.84
	Throughput (veh)	1045.75	1885.84	80.33
	TTS (min)	54235.51	25856.38	-52.33
	TTD (veh-mile)	14984.66	18858.73	47.08
	SAS (mile/hr)	16.58	43.76	208.51

5. CONCLUSION

Speed limits on freeways have been considered as static factors directly affecting traffic safety; however, this study has investigated optimal speed limits as a means of freeway congestion management. The paper has derived theoretical optimal speeds for a stretch of freeway with multiple sections by incorporating a fundamental traffic flow model.

By coupling such advanced systems as ACC and ISA, speed control strategies can be used as an effective control strategy for mitigating congestion. This study has demonstrated the effectiveness of speed control scheme through simulation experiments, under the assumption of a simple traffic flow process in order to show relationship and concept of speed control strategy. However, it can be extended to more complicated systems.

Although this study has provided conceptual benefit and theoretical derivations for optimal speed, how to achieve such optimal speed pattern is another issue. A more realistic analysis for this system can be achieved via a microscopic simulation approach.

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