

A Dynamic Speed Limit Control Approach for Highway Bottleneck Management

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Abstract

Most of the existing traffic control strategies implemented in many countries in the world tend to aim only at improving the efficiency of traffic output. However, decreased the delays and safer traffic are also important outcomes of traffic control. In this study, a dynamic algorithm for variable speed-limit control at toll booth zones is presented that can take full advantage of its dynamic functions and concurrently achieve the objectives of throughput maximization and delay minimization. In this context, field measurements on a real highway tool booth section have been obtained from highway authority in order to determine the pattern of the traffic, which fluctuates all day long. The most important output of the study is the development of an algorithm, which smooth the traffic flow. Developed algorithm has been tested in a microscopic traffic simulation environment. Obtained results have shown that even a standalone speed limit control process can be alleviated the traffic congestion on an urban highway sufficiently.

Keywords: intelligent transportation systems, traffic flow theory, variable speed limit control

1. Introduction

Traffic congestion along the freeway sections are likely to increase in recent years due to the increasing demand over mobility [1]. Almost half of the congestion experienced in the modern world happens virtually every day which can be also defined as "recurring". This is the type of congestion where there are simply more vehicles than roadway. The other half of congestion is caused by temporary disruptions that take away part of the roadway from use namely "nonrecurring" congestion [2]. There are many ways that the congestion can be occurred along the highway. One of the most important reasons of congestion is the bottleneck sections which can be either formed by a lane drop or a temporary occupation of a lane due to an accident, incident or a road work. The disruption of traffic flow can be observed at the vicinity of bottlenecks caused by merging maneuvers. These merging maneuvers tend to create shock wave effects that cause long delays and slow traffic.

Variable Speed Limit systems consist of variable message signs placed on gantries along the freeway and connected to traffic control centre [3]. The variable message signs, rather than traditional static signs, are used to display the regulatory or advisory speed limit, enabling freeway system controllers to dynamically intervene to the corresponding traffic conditions.

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In general, variable speed limit control is implemented to homogenize traffic flow, improve safety, and reduce driver stress. Many variable speed limit control strategies have been put into action in USA, UK, the Netherlands, Germany, Australia, Austria, Japan and Turkey [4].

There are several recent studies investigating the impact of variable speed limit on safety and traffic flow however, much of the focus of VSL system evaluation studies has been on safety [5]. There appears to be even less evidence to suggest that speed control strategy increases traffic flow efficiency. This paper investigates the performance of variable speed limit (VSL) control as an alternative mitigation treatment for freeway recurring traffic congestion. To do this an intercontinental highway section was selected that suffers from recurring traffic congestion caused by lane drop and lane merging in at the toll booth stretch of FSM Bridge in Istanbul.

The remainder of paper is organized as follows: In Section 2 the variable speed limit control and the model predictive variable speed limit control (MP-VSL) will be stated. In the 3rd section the simulation study will be introduced emphasizing the simulation study area, data and simulation procedure. The calibration of traffic model and the results are also given in Section 3. Finally the discussion and the conclusions are drawn in the corresponding sections of this paper.

2. Statement of Model Predictive Variable Speed Limit Control

2.1. Variable Speed Limit Control

The ideal VSL system consists of sensors, variable speed limit signs, variable message signs, and a central processing unit to execute control actions. As shown in Figure 1, VMS are used to inform drivers of the traffic condition ahead and to display the enforced speed limit based on the VSL control strategies.



Figure 1. VSL Control in Istanbul [6].

Depending on the approaching volume, driver compliance rate, and the resulting congestion, the central processing unit that integrates all system sensors and signs will compute the time-varying optimal speed limit for each VMS dynamically and display it in a timely fashion [7].

Common practice over the past several decades for work zone operations is to recommend or enforce a reduced speed limit via variable message signs (VMS), which may or may not respond to fluctuations in approaching traffic demand. To properly respond to traffic conditions and to increase the compliance rate of drivers, traffic professionals in recent years have experimented with variable speed limit (VSL) control in place of the conventional posted speed limit operations in highway work zones [7].

In brief, most existing VSL-related systems have been designed in response to traffic safety concerns but not for improving operational efficiency, such as to maximize the throughput from a work zone segment or to minimize the average delay for vehicles traveling through the entire highway segment plagued by the work zone-imposed traffic queue. Our study intends to address this critical issue with a dynamic VSL control algorithm for highway work zone operations. Our proposed VSL system dynamically adjusts the set of displayed optimal speed limits based on the detected occupancies at the bottleneck section of the freeway, so as to effectively respond to potential demand variation and establish a smoother flow along the stretch.

2.2. Model Predictive Control (MPC)

MPC models predict the change in the dependent variables of the modeled system that will be caused by changes in the independent variables. MPC is an optimal control method applied in a rolling horizon framework. Optimal control has been success-fully applied by several researchers in traffic control over the years [8].

Either optimal control or MPC have the advantage that the controller generates control decisions that are optimal according to a controller-supplied objective function. However, MPC offers some important advantages over conventional optimal control. First, optimal control has an open-loop structure, which means that the disturbances (in our case: the traffic demands) have to be completely and exactly known before the simulation, and that the traffic model has to be very accurate to ensure sufficient precision for the whole simulation. MPC operates in closed-loop, which means that the traffic state and the current demands are regularly fed back to the controller, and the controller can take disturbances into account and correct for prediction errors resulting from model mismatch. Second, adaptivity is easily implemented in MPC, because the prediction model can be changed or replaced during operation. This may be necessary when traffic behavior significantly changes (e.g., in case of incidents, changing weather conditions, lane closures for maintenance). Third, for MPC a shorter prediction horizon is usually sufficient, which reduces complexity, and makes the real-time application of MPC feasible [9].

In our control algorithm a linear regression model is used to predict the occupancies of the next time frame. The time series model can be expressed as;

$$0_{t} = \beta_{1}0_{t-1} + \beta_{2}0_{t-2} + \beta_{3}0_{t-3}$$
(1)

where, Ot is the dependent variable and Ot-1, Ot-2 and Ot-3 are the independent variables to predict

the occupancies of the further time frames. β_1 , β_2 , and β_3 are the coefficients determined with the regression analyses. The result of the regression analyses yield that without an intercept the coefficients are found as 0.6, 0.2 and 0.2 respectively for β_1 , β_2 , and β_3 and the R² is found as 0.96 thus, this model can be considered as highly representative.

2.3. Dynamic VSL Control

To perform an optimal dynamic VSL control, a set of traffic models must capture the complex interactions between traffic-state evolution and all control parameters. In particular, those traffic-state evolution equations should be mathematically formulated to represent the actual operational constraints. As recognized in many studies [3] [10-11] traffic density and speed have been taken as state variables, of which the former is a key factor affecting drivers' choice of speed and the VSL system's selection of appropriate speed limits.

However, instead of taking speed or volume as a control variable occupancy measure is proposed as an optimal control variable of VSL algorithm for congestion alleviation. The algorithm includes the time dependent occupancies and variable speed limit intervals as control variables and parameters. Table 1 shows the VSL strategies employed in this paper. The first VSL strategy is the conventional speed harmonization strategy that keeps the maximum speed limits at 90 km/h. The second strategy takes the occupancy measurements at the downstream section of ramp bottleneck. On the other hand, the third strategy reads the most critical section of the stretch which is just before the entrance of the FSM bridge where 6 lane highways narrows down to 4 lane highway.

Strategy	Occupancy	Posted Speed Limits(km/h)
Speed Harmonization (Strategy 1)	-	90
	0.15	120
Ramp Downstream Control (Strategy 2)	0.2	110
	0.25	100
	0.3	90
	0.35	80
Bottleneck Downstream Control (Strategy 3)	0.1	120
	0.15	110
	0.2	100
	0.25	90
	0.3	80
	0.35	70

Table 1. VSL STRATEGIES

3. Simulation Experiment

There are two ways to evaluate the performance of VSL: field operational tests and computer

simulations. Although field tests provide more realistic results, due to the high costs and time consuming nature, traffic simulation studies are becoming more popular. In this study, widely accepted, discrete, stochastic, time step based microscopic traffic flow simulation software, VISSIM, is employed to test the performance of control strategies and compare their performances. VISSIM utilizes psychophysical car following models which combines a perceptual driver behavior model with a vehicle dynamic model [12].

The VSL control strategies are examined through using the micro-simulation approach. The proposed strategy is evaluated against two alternatives including the base scenario assuming no VSL, a conventional speed harmonization VSL and a newly developed reactive type VSL. The relative effectiveness and benefits are analyzed in terms of selected performance measures.

RTMS (Remote Traffic Microwave Sensor) is a sensor used to collect the data from the section of the highway on which RTMS is set up. The traffic composition and the priorities at the ramp weaving areas are set through the data collected from RTMSs installed by Istanbul Metropolitan Municipality Transportation Authority. Occupancy, long and all vehicle volume and speed data were collected on daily, time and lane basis with RTMS (Figure 2.).



Figure 2. RTMS data collection

The data was collected at a section of O2 highway before crossing the Fatih Sultan Mehmet (FSM) Bridge between the days 06.07.2010-13.07.2010 which does all includes regular days (non-holidays, regular weather conditions, etc.) with the time difference varies between 56-599 seconds but mostly 120 second.



Figure 3: Demonstration of the Bilateral and Trilateral Relationships of Traffic Variables based on Field Data

8 consecutive flows are added which yield to approximately 15 min flow and completed into hourly basis. For the aggregation of the speed data the weighted averages with respect to flows observed are concerned and for the aggregation of the density data the weighted averages with respect to time differences observed are concerned. Refined data is given in Figure 3 and 4.

3.1. Set-up and Calibration

The study corridor is simulated for the afternoon peak hours which start from 17:30 to 20:30 and performance measurement interval is selected as 15 minutes. It is stated in previous studies [4] that, the drivers are highly aggressive and breaking and acceleration values should be inserted as higher than the default values for Istanbul. Lane changing is also highly strong in Istanbul traffic and drivers are frequently cutting in and overtaking.

The car following model is selected as Wiedemann 1999, which has ten driver behavior parameters labeled CC0 - CC9. Several driver behavior parameters are reported to have significant impacts on roadway capacity and speed profiles thus, the parameters need to be optimized to attain the visual conformity and numerical correlation between the observation and simulation [13].

In the model calibration process, model parameters are altered until a qualitative and a quantitative balance between the simulation and the observation is reached. Traditionally, calibration requires several runs based on engineering judgment and experience. Two step calibration procedure is applied in this study, which are; calibration of driving behavior models, and model fine-tuning. The mean target headway and driver reaction time, which are the key user specified parameters in the car-following and lane changing models, can drastically influence overall driver behaviors of the simulation [13]. The calibrated values of the two parameters are 0.6 sec and 1.5 sec in this study. The calibration of ten parameters in car following model could be performed through some optimization techniques in order to achieve the most representative model. However, this is not the focus of this paper. Likewise, the local arterial roads are not included in the studied network hence, route choice is not considered in this calibration process. The required number of runs can be calculated according to the mean and standard deviation of a performance measure of these runs, which is estimated from;

$$N = \left(t_{\alpha/2}\frac{\delta}{\mu\varepsilon}\right)^2 \tag{2}$$

where μ and δ are the mean and standard deviation of the performance measure based on the already conducted simulation runs; ε is the allowable error specified as a fraction of the mean μ ; $t_{\alpha/2}$ is the critical value of the t-distribution at the confidence interval of 1-*a*. It is found that 10 different simulation runs are required. Therefore, the random seeds are chosen by creating 10 random numbers between 0 and 100 are listed in Table 2.

Table 2. Random seeds used in simulation

Number	1	2	3	4	5	6	7	8	9	10
Random Seeds	5	15	25	35	45	55	65	75	85	95

In calibration process GEH index [14] is often used to test the relative difference between observed (Q_o) and simulated (Q_s) link volumes. GEH formula can be calculated with equation (3) and the GEH values are tabulated in Table 3.

$$GEH = \sqrt{(2(Q_o - Q_s)^2)/(Q_o + Q_s)}$$
(3)

The simulation model is acceptable if the GEH scores are smaller than 5 in 85% of the links and smaller than 4 for the sum of all link counts. The GEH scores are below 5 for all the links. **Table 3.** GEH Values

SECTION			
Hours	RAMP	MAINLANE	NETWORK
17.30 - 18.29	2.5	3.0	3.3
18.30 - 19.29	3.2	3.8	4.2
19.30 - 20.29	4.1	4.9	4.4

The volumes are inputted as 15 min exact volumes in order to represent the exact static routing decisions. Desired speed decisions are calibrated along the corridor in order to test the speed limit control in simulation environment. One of the important issues is compliance of drivers to the posted speed limits. However this is not the focus of this study and it is assumed that all the drivers are following the speeds with a 5% upper and lower margin. In order to achieve this in simulation environment the speed profiles are adjusted linearly for every speed limit examined.

3.2. Results

The objective of the freeway traffic control process is to optimize a performance index that

mostly consists of efficiency measures. Performance index can be stated to minimize the travel times, delays, number of stops, or some other parameters such as fuel consumption and environmental pollution or in a more social context the optimization temporal and spatial of equity along the network or a more comprehensive objective that considers all the aspects with suitable weighting. However, only the efficiency properties are investigated for each control strategies in this study.

The first performance measure is selected as total travel time. The Total travel time is calculated in hours for all active and arrived vehicles. In addition to the total travel time, the total delay in hours, the total number of stops and the average speed in km/h are evaluated by averaging values of 15 min. intervals for each simulation run.

Table 4 presents the performance measure of control strategies investigated. It shows that all the traffic control strategies significantly increase the network performance. According to the results obtained (MP-VSL) outperformed the conventional VSL and no control case in all the measures. Nevertheless, even for the conventional VSL, the total delays get smaller values than no control case. The best network performance is attained at Strategy 3 where average speed increase from 30.1 km/h to 35.3 km/h. and almost 8 % decrease in total travel time. With MP-VSL, the total stopped delay, average number of stops per vehicle and average delay per vehicle measures are also reduced significantly.

	Average Delay	Average Number	Average	Average	Total	Total
	Time Per	of Stops Per	speed	stopped delay	stopped	travel
	Vehicle [s]	Vehicle	[km/h]	per vehicle [s]	delay [h]	time [h]
No Control	222.0	1.4	32.8	30.1	491.9	6047.9
Strategy 1	218.0	1.3	33.0	30.0	488.5	6003.6
Strategy 2	208.7	1.3	34.2	28.5	463.9	5853.1
Strategy 3	202.5	1.2	35.3	26.6	413.4	5653.0

 Table 4. Performance Measures of Control Strategies.

The results indicated that the total travel time can be significantly diminished by the examined control method. Table 4 shows the resulting total travel times for each control strategy and the comparison of best scenarios with no control case. From the results for the speed limits of 100 km/h, 90 km/h and 50 km/h, the performance of total travel times, the number of stops and the average speed measures are decreased.

The total delays of achieved with conventional speed limit control still have smaller values when it is compared with no control. This is possibly explained by the fact that speed harmonization may affect the total delays on the traffic network.

4. Discussion

This study demonstrates the potential of implementing traffic control strategies in alleviating the traffic congestion on an urban freeway. Conventional and Model Predictive Variable Speed Limit (MP-VSL) control strategies are analyzed in this paper. The traffic simulation network is modeled in a traffic micro simulation environment and the traffic model is calibrated for the analyses. As indicated by the simulation results, the proposed (MP-VSL) control established better performance than no-control and the other control strategy examined. There are also other control strategies that can be examined for the same experiment setup. Future research is needed to compare the presented methods with the other approaches that have been recently developed, in order to understand the best features of each approach. Additional benefits of this course of research are the insights gained in traffic control and bottleneck formation typologies. Identifying the limits of traffic control strategies would assist in efficiently directing these treatments.

Conclusions

The traffic control strategies evaluated in this paper shows that the total delays along the stretch can be reduced through the increased capacity at bottleneck location. According to the results, the conventional speed limit control strategy performs better than the no control case in every performance measures taken account in this paper. It is considered that the speed harmonization effect can help to alleviate the congestion even without a dynamic control approach. Another interesting result of this analysis is that the (MP-VSL) control strategy increases the effectiveness of the traffic flow referring the total travel time, the total delay, the number of stop and average speed, in a satisfied manner and even performs better than the conventional speed limit control. Especially the remarkable decrease in total delay and average stop delay per vehicle measures shows that the proposed algorithm establishes a smoother traffic flow.

On the other hand, the distribution of the performance increases are one of the issues should be analyzed in detail. The efficiency measures are studied prior to the performance; however there are other measures especially emissions could be further analyzed.

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