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Efficiency analysis of the dynamic traffic control for an urban highway

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Abstract

In this study, dynamic traffic control strategies, namely dynamic ramp metering and dynamic speed limit control, have been examined through microscopic traffic simulation based on site measurements. In this context, the traffic flow data at a particular highway intersection have been analyzed to determine the pattern of the traffic. Then, the traffic model has been built in a traffic micro-simulation software and calibrated with the field data. The foci of the study are to measure the efficiency of the dynamic traffic control strategies and to compare it with the uncontrolled case considering various performance indicators such as total travel time, average delay time per vehicle, and average number of stops per vehicle. For the dynamic ramp metering strategies, the ALINEA (Asservissement Lineaire d'Entree Autoroutiere - French for Linear Utilization for Highway Entrances) control algorithm is implemented with different fixed-time cycle lengths. It has been observed that various ramp metering implementations decreased the average delay time per vehicle up to 30%. The dynamic speed limit control strategies are set according to the occupancy rates that are measured at the bottleneck downstream. The examined speed limit control strategies decreased the average delay time per vehicle to around 7%. The results also revealed that the implemented dynamic traffic control strategies help alleviate congestion by increasing the capacity of the bottleneck section.

Keywords: Intelligent transportation systems; Dynamic ramp metering; Dynamic speed limit control

1 Introduction

Traffic congestion and management have been an important problem for traffic engineers. Traffic congestion along the freeway sections is expected to increase in upcoming years due to the continuous increasing demand of 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 a type of congestion where there are simply more vehicles than roadway capacity. 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 congestion can occur along the highway. One of the most important reasons of congestion is the bottleneck sections which can be formed by either a lane drop or a temporary occupation of a lane due to an accident, incident, or roadwork. 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.

Congestion has a direct effect on travel speed and brings out safety concerns [3,4]. The continuously increasing traffic congestion problem has led to the application of various control strategies. Basically, these are formed by controlling the number of vehicles entering the freeway and/or by changing the speed limit of a designated section along the freeway. Advanced urban traffic networks including both urban roads and freeways utilize control strategies like signal control, ramp metering, variable message signs, and route guidance [5].

This paper investigates the performance of dynamic traffic control strategies as an alternative congestion management tool especially for the freeway recurring traffic congestion. An intercontinental highway section was selected as the study field that suffers from recurring traffic congestion caused by lane drop and a ramp merge just before the toll booth stretch of FSM Bridge in Istanbul.

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The remainder of this paper is organized as follows: In Section 2, the ramp metering control, speed limit control models, and the model predictive control will be presented. Following this section, the simulation study will be introduced emphasizing the simulation study area, data, and simulation procedures. The simulation results will be given in Section 4, and the discussion and the conclusions are drawn in the corresponding sections of this paper.

2 Dynamic traffic control strategies

In order to control traffic in an optimal state, various approaches are proposed by traffic engineers since the 1970s [6]. The increasing demand of automobile use and therefore the use of highways cannot be managed by increasing the supply respectively. It is obvious that resources are limited and it is not feasible to have a capacity which is required for only a limited time. Intelligent traffic control systems are one of the prominent alternatives to road expansion and should be the first option to consider. The models examined in this study are widely used traffic control strategies which are proven to improve traffic conditions by increasing the capacity utilization, namely ramp metering control, variable speed limit control, and model predictive control.

2.1 Ramp metering control

The use of traffic signals on ramps to control the merging on freeways is called ramp metering. Ramp meters are installed to control the rate of vehicles moving into to the mainline traffic; thus, they prevent the critical volume of a freeway in order to control the demand and, moreover, break the platoon of vehicles entering the freeway upstream of the signal to decrease the weaving phenomenon at the merge area.

Ramp metering is a well-known strategy in freeway traffic control. In fact, various techniques of ramp control were used in the late 1950s and through 1970s in Japan and USA [7]. By the early 1990s, the technological advancement both in computing and measurement techniques make more sophisticated ramp metering systems possible to analyze and implement.

Ramp metering strategies could be categorized according to their level of scope ramp metering which are

- local ramp metering (isolated) and
- system-wide (coordinated) ramp metering.

In isolated or local ramp metering, the control system deals with an isolated highway section rather than the whole network. Most of the local ramp metering strategies can be categorized into four types [8]:

- *Demand capacity control*. In this type of control system, metering rate is determined by the upstream volume and downstream capacity. The difference between the upstream volume and downstream capacity determines the metering rate for the next cycle.
- *Upstream occupancy control*. In this strategy, real-time occupancy upstream of the on-ramp is used in order to determine the metering rate for the next cycle.
- *Gap acceptance control*. For gap acceptance control, occupancy measurements from upstream of the ramp are measured to determine the metering rate.
- *Closed-loop local control strategies*. For closed-loop control, system output is fed back and the input is modified with respect to the output. Here the aim is to set the output value at a desired level.

System-wide ramp metering is a control system which considers a network with various sequential or coordinated ramps. Improving traffic flow at a highway intersection may not be sufficient for a relaxation in the whole network. It may also be harmful to the other consecutive segments.

That is why the whole network should be under consideration while optimizing the traffic flow. For that purpose, system-wide (coordinated) ramp metering control strategies are taken into account. Examples of system-wide ramp metering control strategies are FLOW [9], Zone (Minnesota) algorithm [10], Stratified Zone (new Minnesota) algorithm [11], Helper [12], METALINE [13], and SWARM [14].

2.2 Variable speed limit control

Variable speed limit systems consist of variable message signs placed on gantries along the freeway and connected to a traffic control center. 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. 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 [15]. Much of the focus of VSL system evaluation studies has been on safety [16]. There appears to be even less evidence to suggest that speed control strategy increases traffic flow efficiency. Papageorgiou et al. [17] utilized the data of a German motorway to investigate the impact on aggregate traffic flow behavior and efficiency.

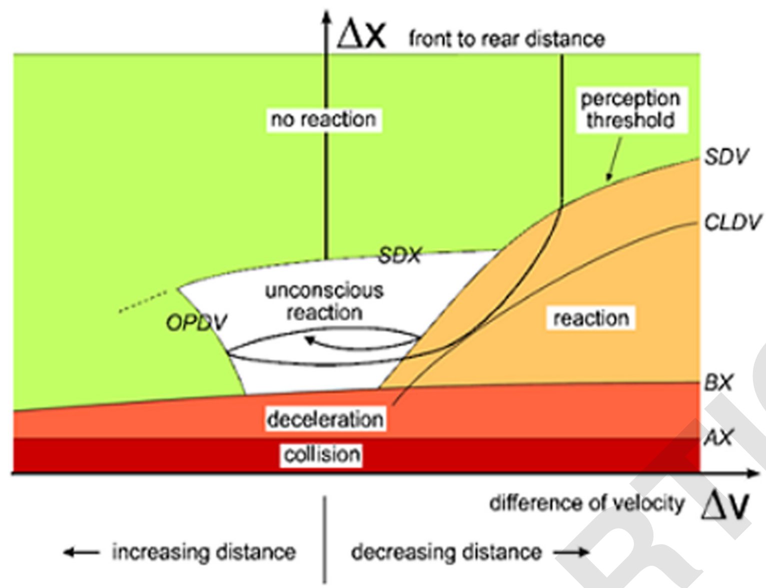

Figure 1 Wiedemann's car-following model [22].

2.3 Model predictive control

Model predictive control (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 successfully applied by several researchers in traffic control over the years [9,18].

Either optimal control or MPC has the advantage of having the controller generate 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 a closed-loop structure, 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, and lane closures for maintenance).

Third, for MPC, a shorter prediction horizon is usually sufficient, which reduces complexity and makes the real-

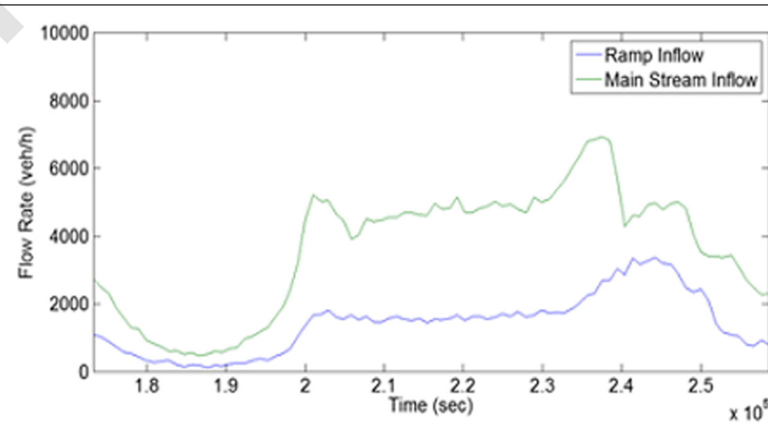

Figure 2 Flow data for 8 July 2010 (Thursday).

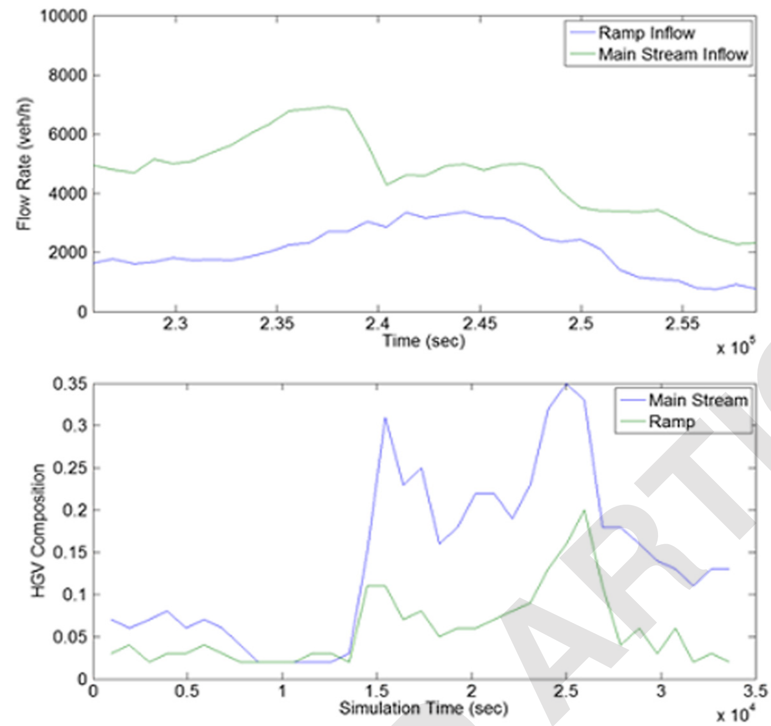

Figure 3 Flow data (up) HGV composition for 8 July 2010 (Thursday).

time application of MPC feasible [9]. In this study, a linear regression model is used to predict the occupancies of the next time frame.

3 Microscopic traffic simulation

There are three main classifications of traffic models according to the approach used in the analysis. One of them is the classification with respect to the given input. If traffic is invariant over time, this type of simulation models the steady-state average traffic conditions and is stated as static; if traffic changes over time, this type models the variant nature of traffic and is stated as dynamic.

Another classification of traffic models is defined by their statistical point of view. If the outputs of the traffic simulations are different by their executions, i.e., if there is randomness at the modeling process, it is called stochastic modeling of traffic. If the simulations demonstrate the same output in every execution, it is called deterministic modeling of traffic. The last and the most important classification of traffic models is the level of

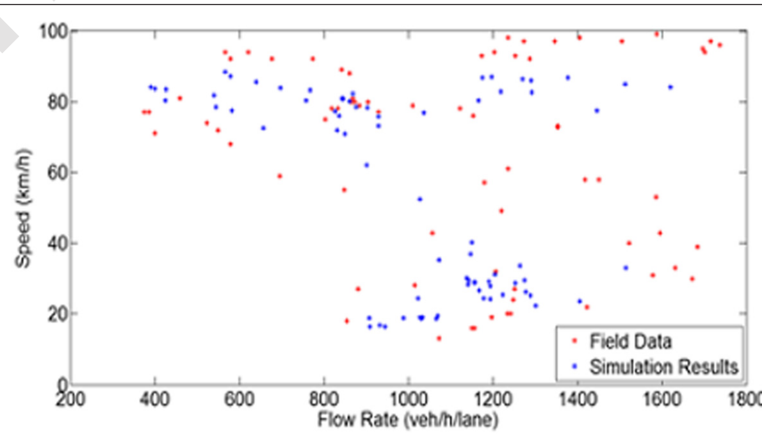

Figure 4 Speed-flow calibration/verification results for the entire stretch.

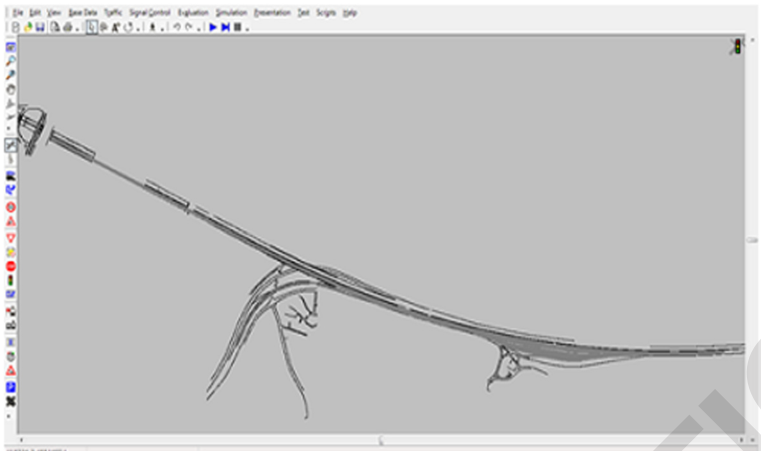

Figure 5 Study network generated in PTV VISSIM.

detail in terms of traffic flow, which are microscopic, mesoscopic, and macroscopic simulations.

3.1 Simulation model

In this study, the microscopic traffic simulations are performed by using PTV VISSIM simulation software. PTV VISSIM is a microscopic simulation program based on the driving behavior model of Wiedemann proposed in 1974 [19] and in 1999 [20]. PTV VISSIM is developed by PTV AG (Planung Transport Verkehr Aktiengesellschaft) and written in C++ considering guidelines of object-oriented programming (OOP) [21,22].

PTV VISSIM enables not only monitoring of the actual state of traffic but also simulation and evaluation of the macroscopic traffic variables as in real life. In many cases, the precautions, suggestions, or changes are done with regard to the simulation results. PTV VISSIM is also able to demonstrate the multimodal structure of the area such as public transit busses, heavy rail, or pedestrians, which is defined by the user. There are two main driving behaviors which are logically based on longitudinal and lateral movements, since all the movements on the road surface can be represented as a superposition of those two main movements.

The Wiedemann car-following models used for longitudinal movements in the PTV VISSIM simulation program are mainly based on the psychophysical driving behavior of the drivers.

Four main phases of driving are defined as free driving, approaching, following, and braking. These states are represented in Figure 1.

Lateral movements are mainly considered in lane changing movements in PTV VISSIM. There are two main lane change types considered - which lane is changing from the fast lane to the slow lane and from the slow lane to the fast lane - which are highly considered in [22].

3.2 Study field and data set

Levent ramp of Istanbul Outer Beltway (O-2) was determined as the study field. The data were collected by remote traffic microwave sensors (RTMS) between 6 July 2010 (Tuesday) and 13 July 2010 (Tuesday) which includes regular days (non-holidays, regular weather conditions, etc.).

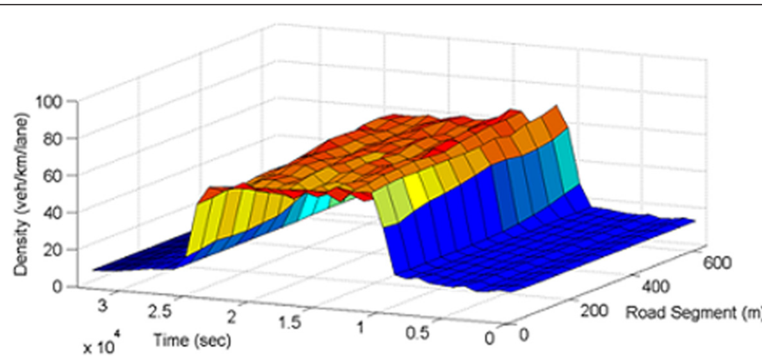

Figure 6 No-control density profile.

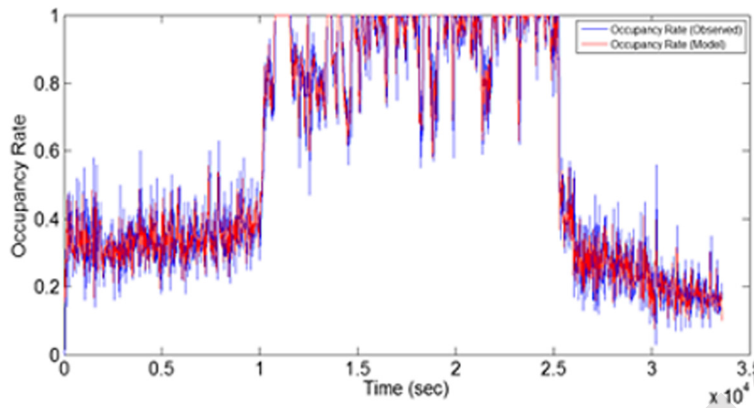

Figure 7 Occupancy rate prediction model.

For vehicle input scenario, 8 July 2010 (Thursday) 14:45:28 to 23:48:56 is selected where afternoon peak, low inflow, moderate inflow, and high inflow for both main stream and ramp are seen. Flow data for the whole day (8 July 2010), for the selected hours and heavy goods vehicle (HGV) percentage in traffic composition change, are shown in Figures 2 and 3, respectively.

3.3 Calibration, verification and implementation of proposed strategies

A speed-volume diagram is plotted for calibration in order to check and validate the accuracy of the speed-volume diagram between the simulation results and field observations as proposed in [21]. These diagrams are very useful for calibration because they contain information about a broad range of traffic situations. In particular, they show how the traffic flow behaves around capacity. This is the reason why these speed-flow diagrams are often used for comparing simulation results with real-world data. Another purpose for looking at the speed-volume scatter plots is to see whether the desired volumes can pass through an intersection with the desired speeds or not. It is found that the simulation is valid and accurate by looking at the speed-volume diagram. The results are presented in Figure 4.

The linearized local-feedback control algorithm ALINEA (Asservissement Lineaire d'Entree Autoroutiere - French for Linear Utilization for Highway Entrances), proposed by Papageorgiou et al. in 1991 [1,17], is used in this study. This strategy aims to keep the occupancy rate at the level of the desired occupancy rate which is generally taken as 0.30, as proposed by the authors. The main step of this strategy is given as follows:

$$r(t+\Delta t) = r(t) + (K_r(\hat{o} - o(t+\Delta t))$$

where $r(t + \Delta t)$ is called the metering rate to release to the downstream at the next cycle, $r(t)$ is the metering rate which is released at the current cycle, K_r is a regulator parameter which is taken generally as 70 by the authors and the applicators of this algorithm, $\hat{o}$ is the desired occupancy rate, and $o(t + \Delta t)$ is the predicted occupancy for the next cycle. There are also other closed-loop local control strategies such as fuzzy logic control [12].

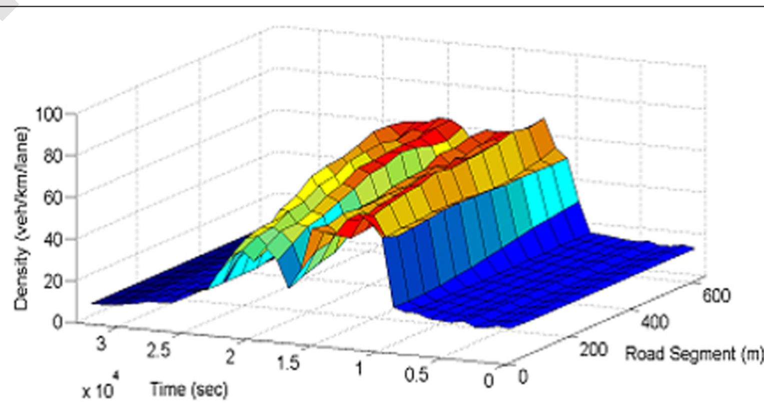

Figure 8 Density profile for ramp metering approach (ALINEA 1).

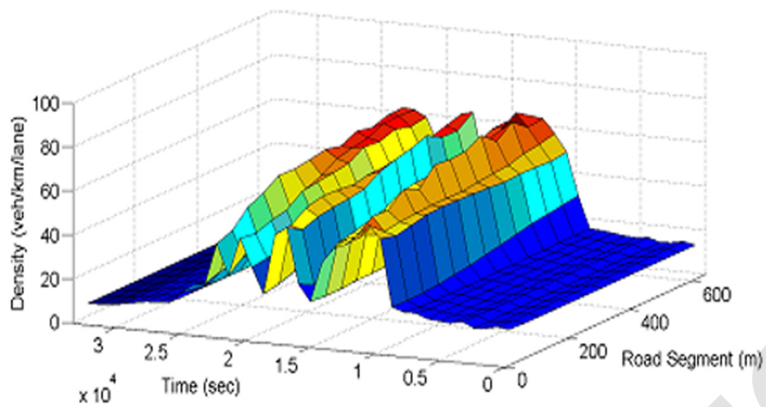

Figure 9 **Density profile for ramp metering approach (ALINEA 2).**

For the study field and data described, the network is generated, and the vehicle inputs (traffic volumes and vehicle composition) are entered as proposed. The simulation interface is shown in Figure 5. Random seeds are selected in a range varying from 5 to 95 with five increments, and the arithmetic average is taken into account while interpreting the results. The downstream link is segmented into 50-m multiple segments, and from the link evaluation option, density is collected in order to plot the density profile along the downstream link. The result is demonstrated in Figure 6 for the no-control case.

For the evaluation process to be used in dynamic traffic flow control approaches, data collection points are positioned at the 50th meter of the downstream link as proposed in [14].

Occupancy rates are measured with a time interval of 20 s since one of the ramp metering approach and all the variable speed limit approaches have the cycle time of 20 s. For the obtained results, a regression model is proposed in order to predict the traffic and to take precautions. The regression model is as follows:

$$o(t + \Delta \mathrm{t}) = c_0 o(t) + c_1 o(t\text{–}\Delta \mathrm{t}) + c_2 o(t\text{–}2\Delta \mathrm{t})$$

where $o(t + \Delta t)$ is the next occupancy rate which is predicted to be measured in the next cycle; $o(t)$ is the current occupancy rate which is measured in the same time interval; $o(t)$, $o(t - \Delta t)$, and $o(t - 2\Delta t)$ are the occupancy rates which have been measured in the past first, second, and third time intervals, respectively; and *ci*'s are normalized constants to be determined. After the regression analysis, $c_0 = 0{:}29$, $c_1 = 0{:}02$, and $c_2 = 0{:}69$ are taken, and R^2 is found as 0:96; thus, this model can be considered as highly representative. The occupancy rate prediction model is shown in Figure 7.

In order to apply the ALINEA algorithm to the Vehicle Actuated Programming (VAP) module for PTV VISSIM, in the simulation, a 5-m detector is placed at the 50th meter of the bottleneck downstream. The green times are calculated as

$$\text{Green time}\,(t + \Delta t) = \frac{r(t + \Delta t)}{r_{\text{sat}}} \times \text{Cycle time}$$

for each cycle where r_{sat} is the saturated flow and taken as 2,000 vehicles/h.

The two versions of the ALINEA approach are coded in VAP. In the first version (ALINEA 1), cycle time t is taken as 20 s and the minimum green time is taken as 10 s. The density profile for the first approach is demonstrated in Figure 8.

In the second version (ALINEA 2), cycle time t is taken as 15 s and the minimum green time is taken as 5 s. The density profile for the second approach is demonstrated in Figure 9.

Instead of taking speed or volume as a control variable, the occupancy measure is proposed as an optimal control variable for the dynamic speed limit control strategy. The algorithm includes the time-dependent occupancies and variable speed limit intervals as control variables and parameters. Table 1 shows the dynamic speed limit control

Table 1 Dynamic speed limit control strategies

Dynamic speed limit control strategies	Occupancy (%)	Speed (km/h)
DSLC 1	15	120
	20	110
	30	90
	35	80
DSLC 2	10	120
	15	110
	20	100
	25	90
	30	80
	35	70

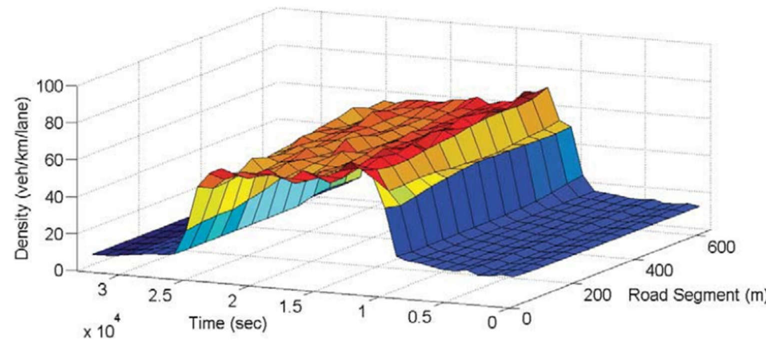

Figure 10 Density profile for dynamic speed limit control 1 (DSLC 1).

strategies employed in this study. The dynamic speed limit control strategies take the occupancy measurements at the downstream section of the ramp bottleneck, which is the most critical section of the stretch that is located just before the entrance of the FSM Bridge where six-lane highways narrow down to four-lane highways. The density profiled for the speed limit control strategies is demonstrated in Figures 10 and 11.

4 Dynamic traffic control simulation results

The performance measures are determined as the average delay time per vehicle, average number of stops, average speed, average stopped delay per vehicle, total delay time, number of stops, total stopped delay, and total travel time.

The first dynamic ramp metering approach, ALINEA 1, managed to decrease the average delay time per vehicle by 32%, average number of stops by 21%, average stopped delay per vehicle by 34%, total delay time by 32%, number of stops by 21%, total stopped delay by 34%, and total travel time by 20%. This approach also increased average speed of vehicles by 24%. The second dynamic ramp metering approach, ALINEA 2, accomplished to reduce the average delay time per vehicle by 29%, average number of stops by 21%, average stopped delay per vehicle by 35%, total delay time by 30%, number of stops by 22%, total stopped delay by 35%, and total travel time by 18%. This approach also increased the average speed of vehicles by 21%.

The simulation results also show that the first dynamic speed limit control strategy (DSLC 1) decreased the average delay time per vehicle by 7%, average speed of vehicles by 3%, average stopped delay per vehicle by 6%, total delay time by 8%, number of stops by 1%, and total stopped delay by 7%. However, the total travel time could not be significantly increased with this control strategy. For the second dynamic speed limit control strategy (DSLC 2), it decreased the average delay time per vehicle by 7%, average speed of vehicles by 6%, average stopped delay per vehicle by 7%, total delay time by 8%, number of stops by 2%, and total stopped delay by 9%. The total travel time remained the same for this control strategy as well.

5 Conclusions

Two main dynamic traffic control strategies are proposed and examined for the traffic congestion management for Istanbul Outer Beltway (O-2). For the ramp metering strategy, different versions of the ALINEA control algorithm are employed. The simulations are run multiple times in order to check for the consistency of

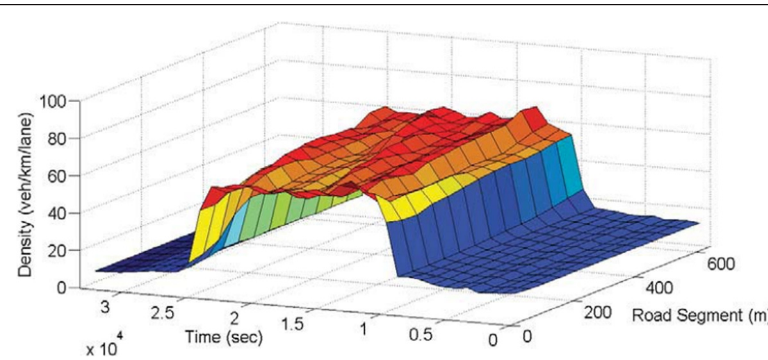

Figure 11 Density profile for dynamic speed limit control 2 (DSLC 2).

the random seeds which is also proposed in the PTV VISSIM manual [22].

The results indicated that especially the total delays can be significantly diminished by the examined control strategies. The best results are obtained for total travel time in the ramp metering approach whose cycle time is equal to 15 s and minimum green time to 5 s.

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are not included within the context of this study. However, it is obvious that communication technologies are increasingly advancing and the effects of communication on traffic control performance are considered as a future work besides the investigation of coordinative dynamic ramp metering approaches, dynamic lane closure, or various variable speed limit approaches.

Competing interests
The authors declare that they have no competing interests.

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