Localized Switching Ramp-Metering Controller with Queue Length Regulator for Congested Freeways

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Abstract—In this paper, we present a novel switching traffic-responsive ramp-metering controller that suits the different traffic dynamics under different congestion conditions—free-flow or congested. The approach of multirate linear quadratic control with integral action (LQI) is employed to compensate for disturbances and accommodate the difference between the model sampling time and the metering-rate updating time interval. In addition, a queue length regulator is designed to limit the queue within the ramp storage capacity and improve the performance of the currently used ad hoc “queue-override” scheme. A local ramp-metering control strategy is proposed to achieve the control goal of reducing the congestion’s spatial and temporal span, using locally available information. Test results on a calibrated cell transmission model (CTM) based macroscopic traffic simulator have demonstrated the performance and effectiveness of the switching ramp-metering controller, the queue length regulator, and the control strategy. The switching metering controller tracks the desired mainline density profiles in both free-flow and congested conditions. Under the localized control strategy, the Total Vehicle Delay is saved by 7.7%, while the Total Vehicle Time is reduced by 5.7%, in the CTM traffic simulator.

I. INTRODUCTION

Freeway traffic congestion has been a major problem in today’s metropolitan areas. It occurs regularly during commuting hours. In addition, non-recurrent congestion often takes place as a result of incidents, road work, or public events. Congestion causes inefficient operation of freeways, waste of resources, increased pollution, and intensified driver fatigue.

The 2004 Urban Mobility Report [1] finds: “Congestion has grown everywhere in areas of all sizes. Congestion occurs during longer portions of the day and delays more travelers and goods than ever before.” In the report, the authors have calculated that in 2002, congestion costed the Americans 3.5 billion hours of delay and 5.7 billion gallons of wasted fuel, with an equivalent monetary cost of $63.2 billion.

On-ramp metering has been widely used as an effective strategy to increase the freeway operation efficiency. It has been recommended to the Federal Highway Administration as the No. 1 tool to address the congestion problem, other than adding more capacity to the transportation infrastructures [2]. It has been reported that ramp metering was able to reduce the delay by 101 million person-hours in 2002, approximately 5% of the freeway delay on the freeways where ramp-metering is in effect [1].

In this paper, we will design a novel switching ramp-metering controller that employs different feedback structures depending on whether the freeway is in free-flow or congested mode. It has been known that the traffic dynamics behave differently under free-flow or congested condition. This leads to the different controllability and observability properties for the free-flow or congested traffic [3]. It is thus natural to design different ramp-metering controllers under different congestion modes.

In addition to the switching traffic-responsive ramp-metering controller, we will design a PI regulator to limit the on-ramp queue within the storage capacity and to prevent the excessively long queue to interfere with the surface street traffic. This PI regulator will have a better performance than the currently used “queue-override” scheme.

We will also propose a localized control strategy for the switching metering controller and the queue length regulator to achieve the goal of reducing the spatial and temporal span of the congestion.

Test results of these controllers on a calibrated macroscopic traffic simulator will be presented.

II. PERFORMANCE MEASURES

In order to quantitatively evaluate the performance of a given freeway segment, some measures need to be defined. All the quantities are defined for the time period $T$ and the freeway segment $L$.

- $D_{V,\text{tot}}$: Total Vehicle Distance, which is defined as the sum of the distance traveled by all the vehicles in $L$ within $T$.
- $T_{V,\text{tot}}$: Total Vehicle Time, which is the sum of the time that is spent by all vehicles in $L$ within $T$. It includes the time spent by vehicles while waiting in the on-ramp queues.
- $DL_{V,\text{tot}}$: Total Vehicle Delay, which is the difference between the Total Vehicle Time and the time that would be spent by all the vehicles if there were no congestion. Therefore, $DL_{V,\text{tot}} = T_{V,\text{tot}} - D_{V,\text{tot}}/v_0$, where $v_0$ is the nominal free-flow speed.
- $\bar{v}_{V,\text{tot}}$: Average Total Vehicle Speed $\bar{v}_{V,\text{tot}} = D_{V,\text{tot}}/T_{V,\text{tot}}$.

III. SWITCHING-MODE MODEL AND CONTROLLABILITY

In the previous work [3], we piecewise linearized the cell transmission model [4], [5] and derived a switching-mode traffic model. Depending on the congestion condition in a freeway section, such as the one shown in Fig. 1, the traffic is in a different mode, e.g., free-flow or congested. In each mode, the vehicle densities in the cells, as denoted by 1–4 in the figure, evolve according to a different set of difference equations.
In free-flow mode,
\[
\begin{bmatrix}
\rho_1 \\
\rho_2 \\
\rho_3 \\
\rho_4
\end{bmatrix}
(1 + t) =
\begin{bmatrix}
1 - \frac{\nu_1 T_r}{l_i} & 0 & 0 & 0 \\
\frac{\nu_2 T_s}{l_i} & 1 - \frac{\nu_2 T_s}{l_i} & 0 & 0 \\
0 & 0 & 1 - \frac{\nu_3 T_s}{l_i} & 0 \\
0 & 0 & 0 & 1 - \frac{\nu_4 T_s}{l_i}
\end{bmatrix}
\begin{bmatrix}
\rho_1 \\
\rho_2 \\
\rho_3 \\
\rho_4
\end{bmatrix}
(1) +
\begin{bmatrix}
\frac{T_r}{l_i} & 0 & 0 & 0 \\
0 & \frac{T_s}{l_i} & 0 & 0 \\
0 & 0 & \frac{T_s}{l_i} & 0 \\
0 & 0 & 0 & \frac{T_s}{l_i}
\end{bmatrix}
\begin{bmatrix}
\rho_{sat1} \\
\rho_{sat2}
\end{bmatrix}
(2)
\]

\[
= A(1)q(t) + B_s(1)\tilde{q}(t),
\]

where \(\rho_i\) is the vehicle density in cell \(i\), \(q_{m1}\) and \(q_{m2}\) are the mainline entering and exiting flows, respectively, \(r\) is the on-ramp flow, \(\beta\) is the split ratio of the off-ramp flow, \(l_i\) is the length of cell \(i\), and \(T_s\) is the sampling time.

In congested mode,
\[
\begin{bmatrix}
\rho_1 \\
\rho_2 \\
\rho_3 \\
\rho_4
\end{bmatrix}
(1 + t) =
\begin{bmatrix}
1 - \frac{\nu_1 T_r}{l_i} & 0 & 0 & 0 \\
\frac{\nu_2 T_s}{l_i} & 1 - \frac{\nu_2 T_s}{l_i} & 0 & 0 \\
0 & 0 & 1 - \frac{\nu_3 T_s}{l_i} & 0 \\
0 & 0 & 0 & 1 - \frac{\nu_4 T_s}{l_i}
\end{bmatrix}
\begin{bmatrix}
\rho_1 \\
\rho_2 \\
\rho_3 \\
\rho_4
\end{bmatrix}
(3) +
\begin{bmatrix}
\frac{T_r}{l_i} & 0 & 0 & 0 \\
0 & \frac{T_s}{l_i} & 0 & 0 \\
0 & 0 & \frac{T_s}{l_i} & 0 \\
0 & 0 & 0 & \frac{T_s}{l_i}
\end{bmatrix}
\begin{bmatrix}
\rho_{sat1} \\
\rho_{sat2}
\end{bmatrix}
(4)
\]

\[
= A(2)q(t) + B_s(2)\tilde{q}(t) + B_f(2)\rho_f,
\]

where \(\rho_f\) is the jam density (maximum allowable density) in cell \(i\).

It should be noted that the traffic dynamics are very much different in different modes, which is evidenced by the structures of the “A” matrices in (1) and (3): In free-flow mode, the “A” matrix is lower bi-diagonal, and thus the vehicle densities in the downstream cells are affected by those in the upstream cells, i.e., the information travels from upstream to downstream; In congested mode, the “A” matrix is upper bi-diagonal, and the vehicle densities in the upstream cells are affected by those in the downstream cells, i.e., the information travels from downstream to upstream.

This observation is critical to the design of an on-ramp metering algorithm, because it determines a system’s fundamental properties of controllability and observability. A simple calculation reveals that when a freeway section is in free-flow mode, the on-ramp can control the vehicle densities downstream, while in congested mode, an on-ramp controls the vehicle densities upstream. Therefore, in different mode, different feedback structure has to be employed for the metering controller, as shown in Fig. 2.

Although the congestion modes or the cell vehicle densities are not observed or measured directly, we have designed and implemented a mixture Kalman filter (MKF) based estimator [6], [7] on the switching-mode traffic model that is able to accurately estimate these quantities in real time. The estimated congestion mode is used to determine the appropriate control structure, and the estimated vehicle densities are used as feedback.

IV. MULTIRATE LQI DESIGN FOR THE RAMP-METERING CONTROLLER

In either of the congestion modes, the difference equations governing the evolution of the cell vehicle densities can be written as
\[
\rho(t + 1) = A\rho(t) + B_r r(t) + B_m q_m(t) + B_f \rho_f,
\]

where \(r(t)\) is the on-ramp flow, \(q_m(t)\) are the mainline flows, and \(\rho_f\) are the jam densities.

The desired densities \(\bar{\rho}\) have to satisfy the steady state condition
\[
\bar{\rho} = A\bar{\rho} + B_r \bar{r} + B_m \bar{q}_m + B_f \bar{\rho}_f,
\]

where \(\bar{q}_m\) is the nominal mainline flow. Thus the error dynamics
\[
\tilde{\rho}(t + 1) = A\tilde{\rho}(t) + B_r r(t) - B_r \bar{r} + B_m \bar{q}_m(t).
\]

Let
\[
z(t + 1) = \tilde{\rho}(t + 1) - \tilde{\rho}(t),
\]

and
\[
u(t + 1) = r(t + 1) - r(t).
\]
We have
\[ z(t + 1) = Az(t) + Bu(t) + B_m(q_m(t) - q_m(t - 1)), \]  
(10)
and
\[ \rho(t + 1) = \rho(t) + Az(t) + Bu(t) + B_m(q_m(t) - q_m(t - 1)). \]  
(11)

Considering that in the steady state, \( q_m(t) \) varies slowly, we neglect the \( B_m(q_m(t) - q_m(t - 1)) \) terms and combine the two equations together
\[ \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}(t + 1) = \begin{bmatrix} I & A \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}(t) + B_B u(t), \]
(12)
and write them in a more compact form as follows:
\[ \begin{bmatrix} \dot{z} \\ z \end{bmatrix}(t + 1) = A \begin{bmatrix} \dot{z} \\ z \end{bmatrix}(t) + B_B u(t). \]  
(13)

We would like to synthesize a control law
\[ u(t) = -K(t) \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}(t) \]
(14)
that minimizes the cost function
\[ J = \frac{1}{2} \sum_{t=0}^{\infty} \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}^H(t) \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}(t) + u^H(t)Ru(t) \]
\[ = \frac{1}{2} \sum_{t=0}^{\infty} \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}^H(t)Q \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}(t) + u^H(t)Ru(t). \]  
(15)

This problem can be easily solved using the algebraic Riccati equation. This approach is often referred to as the LQI (LQ with Integral action) method.

The actual control input
\[ r(t) = r(t - 1) - K(t) \begin{bmatrix} \dot{\rho} \\ z \end{bmatrix}(t) \]
(17)
Due to the geometry constraints on the cell lengths, we have chosen the sampling time of the model to be 2 seconds. However, the control variable \( r(t) \) can only be updated every 30 seconds in the field. As a consequence, we have to employ a multirate approach to the LQI method.

We assume that the actual control input \( r(t) \) is updated every \( p \) short time periods (STP’s), which is 2 seconds in our problem. The virtual control \( u(t) \) as defined in (9) can only be inject in the expanded system (13) every \( p \) STP’s, i.e., \( u(t) \) is nonzero only every \( p \) STP’s. Equivalently, instead of letting \( u(t) \) be zero, we can let \( B(t) \) be zero and have a periodic dynamic system (13) in which
\[ B(t) = \begin{cases} B, & \text{when } t = np \text{ for some } n \in Z, \\ 0, & \text{when } t \neq np \text{ for any } n \in Z. \end{cases} \]  
(18)

In order to synthesize the optimal controller (14) for this periodic system, we have to solve the periodic algebraic Riccati equation
\[ P(t) = A^H(t)P(t + 1)A(t) - A^H(t)P(t + 1)B(t)(R(t) + B^H(t)P(t + 1)B(t))^{-1}B^H(t)P(t + 1)A(t) + Q(t) \]
(19)
for a periodic solution
\[ P(t + p) = P(t). \]  
(20)

And the optimal control gain
\[ K(t) = (R(t) + B^H(t)P(t + 1)B(t))^{-1}B^H(t)P(t + 1)A(t). \]  
(21)
Given \( P(p) \), it is straightforward to calculate
\[ P(1) = (I + A + \cdots + A^{p-2})^H Q (I + A + \cdots + A^{p-2}) + (A^{p-1})^H P(p)(A^{p-1}). \]  
(22)
Then we have
(23)
where
\[ A_p = A_p^H = A_p, \]
\[ B_p = A_p^{p-1} B_p. \]
\[ Q_p = \left( \sum_{i=0}^{p-1} A_i^H \right) Q \left( \sum_{i=0}^{p-1} A_i \right), \]
\[ R_p = R + \left( \sum_{i=0}^{p-2} A_i^H \right) B \left( \sum_{i=0}^{p-2} A_i \right) B, \]
and
\[ S_p = A_p^{p-2} \left( \sum_{i=0}^{p-2} A_i^H \right) Q \left( \sum_{i=0}^{p-2} A_i \right) B. \]
Note that (23) is in the standard form of a discrete-time algebraic Riccati equation. The resulting periodic control gain is given by
\[ K(t) = \begin{cases} K_p, & \text{when } t = np \text{ for some } n \in Z, \\ 0, & \text{when } t \neq np \text{ for any } n \in Z, \end{cases} \]  
(24)
where
\[ K_p = (R_p + B_p^H P(p) B_p)^{-1}(B_p^H P(p) A_p + S_p). \]
Another issue that needs to be addressed is saturation. The districts in the California Department of Transportation (Caltrans) have established acceptable maximum and minimum metering rates. The “one vehicle per green” policy and typical driver and vehicle response time determine the green phase length of the metering signal to be 2 seconds. Similarly, the minimum length of the red phase is also 2 seconds. In addition, to avoid the increased probability of signal violation when drivers wait too long, the red phase length is usually limited to 18 or 13 seconds. Therefore, the maximum metering rate is usually 900 vehicles per hour per metered lane (vphpl), and the minimum metering rate is 180 or 240 vphpl.

On the other hand, the set metering rate may not be realized when the arriving rate of the vehicles (the demand) is less than the metering rate, and there are not sufficient number of vehicles waiting in the queue. Therefore, the control input \( r(t) \)
has to be saturated to not only the established maximum and minimum values, but also the number of available vehicles. In order to increase the response time of the integral control, some sort of “anti-windup” scheme has to be implemented.

Similarly to ALINEA [8], we distinguish the desired metering rate \( r_c(t) \), which is set by the controller, and the realized on-ramp flow \( r(t) \), which is measured by the entrance loop detector, and modify the control algorithm (17) to be

\[
r_c(t) = r(t - 1) - K(t) \left[ \bar{\rho} / z \right](t),
\]

and

\[
r_c(t) = \min\{r_{\text{max}}, \max[r_{\text{min}}, r_c(t)]\}
\]

V. ON-RAMP QUEUE LENGTH REGULATOR

Whenever the on-ramp demand \( d(t) \) exceeds the desired metering rate \( r_c(t) \), a queue will form. However, the storage capacity of an on-ramp is often very limited. Without proper control, the vehicle queue length will quickly exceed this capacity, causing the vehicles to spill over into the surface streets and interfere with the street traffic.

The current practice to regulate the queue length is the so-called queue-override. A typical loop detector and signal configuration of an on-ramp is shown in Fig. 3. In the queue-override scheme, the signal controller compares the occupancy measurement of the queue detector with a threshold to determine whether the queue has reached the queue detector. If the queue detector occupancy is above the threshold, the metering rate is increased by a certain level, e.g., 120 vphl, every time interval (e.g., 30 seconds). When the queue detector occupancy falls below the threshold, the metering rate is reset to the value determined by the controller. This queue-override scheme can be viewed as an integral control with a saturated integrating rate and resetting.

The queue length dynamics is modeled as a simple integrator:

\[
l(t + 1) = l(t) + T_p (d(t) - r(t)) \quad \text{subject to } l \geq 0,
\]

where \( l(t) \) is the queue length (in number of vehicles), \( d(t) \) is the demand (the entering flow to the queue), and \( r(t) \) is the on-ramp flow entering the mainline (the leaving flow of the queue).

A simple analysis shows that the integral control alone on an integrator is not asymptotically stable. A proportional action is needed, i.e.,

\[
r_c(z) = \left( k_p + \frac{k_1}{z - 1} \right) \bar{l}(z),
\]

which is written in the transfer function form. In the design of the PI queue length regulator, we treat \( d(t) \) as an external disturbance and \( r(t) \) as the control variable. The closed-loop sensitivity function from the disturbance to the output

\[
\frac{\bar{l}(z)}{d(z)} = \frac{T_s(z - 1)}{(z - 1)^2 - k_p T_s z + (k_1 - k_p) T_s}.
\]

Proper PI gains \( k_p \) and \( k_1 \) can be selected using the root locus method. Furthermore, the anti-windup and saturating mechanisms in (25) and (26) need to be implemented in the queue length regulator too.

In the field, the queue length feedback that is needed by the regulator is not available, because there is no sensing device to measure it. However, in this paper, we assume that we have this measurement, since the macroscopic traffic simulator is able to provide it. We are also designing an estimator for the queue length, using the field available quantities.

VI. LOCALIZED RAMP-METERING STRATEGY

In addition to the switching ramp-metering controller and the queue length regulator, a control strategy is still needed to achieve best freeway performance. For example, the desired mainline density profiles and the desired queue lengths need to be defined. Gomes and Horowitz [9], [10] have formulated a linear program that minimizes the so-called generalized total travel time with explicit queue length constraints. This linear program is based on a modified version of the cell transmission model and produces a set of mainline densities, time-of-the-day ramp-metering rates and queue lengths as the solution, using the predicted traffic demands. These quantities can be used as the desired profiles in the switching controller and queue length regulator.

However, a localized ramp-metering strategy is also desired for the reasons of less algorithmic complexity, lower computational requirement, and higher robustness to the changing traffic conditions such as the unpredicted demands.
The main goal of freeway traffic control is to limit the spatial and temporal span of the congestion, i.e., to slow down the congestion propagation toward the upstream and to speed up the congestion wavefront moving downstream, in another word, to make the wavefront propagation speed \( v_w \) larger.

From the kinetic-wave traffic theory, for a congestion wavefront and a freeway fundamental diagram (flow-density relationship) shown in Figures 4(a) and 4(b), respectively, the propagation speed of the congestion wavefront

\[
v_w = \frac{q_2 - q_1}{\rho_2 - \rho_1}.
\]

where \( q_1 \) and \( q_2 \) are the flows at the points 1 and 2, respectively, and \( \rho_1 \) and \( \rho_2 \) are the densities at the points 1 and 2, respectively.

It can be seen from the above analysis that the local ramp-metering control should move the congested point (the point 2) to the left on the fundamental diagram, i.e., decrease the vehicle density. On the other hand, if there is no local congestion, vehicles can be allowed to enter the mainline as fast as possible, so long as not to induce congestion. Therefore, we choose the set-point of the feedback ramp-metering controller to be the critical density \( \rho_c \), i.e., the density at which the congestion is about to form.

In order to utilize all of available storage capacity on the ramp, it is natural to choose the set-point for the queue length regulator to be the maximum queue length. On the other hand, a long on-ramp queue is also desired for the purpose of deterring short-distance travelers from using the freeway, thus making the freeway capacity available to long-distance travelers.

It has to be noted, however, that the objectives of the queue length regulator and the ramp-metering controller conflict with each other: When the mainline traffic is light, the ramp-metering controller allows vehicles to enter the mainline as fast as possible, resulting in a short queue; at the same time, the queue length regulator is trying to accumulate the vehicles to form a long queue. When the mainline traffic is heavy, the ramp-metering controller only allows vehicles to enter at a slow rate and the queue extends quickly beyond the limit; the queue length regulator will have to increase the metering rate to dissipate the queue until it reaches the acceptable length.

Considering these factors, we choose to set the metering rate at the larger of the two valuess determined by the feedback metering controller and the queue length regulator.

VII. TEST SITE

A segment of Interstate 210 Westbound in Pasadena, California, as shown in an aerial photo in Fig. 5, has been selected as the testbed for new ramp-metering algorithms. It is approximately 14 miles long, from Vernon Avenue (Mile Post 39.159) to Fair Oaks Avenue (Mile Post 25.4). This site was selected as the preferred test location for the following reasons:

1) It is a heavily used freeway segment that experiences severe recurring congestion and can benefit greatly from ramp-metering strategies that reduce congestion and improve total travel time.

2) I-210 has most of the necessary infrastructure, such as loop detectors, on-ramp metering signal controllers, and a centralized advanced traffic management system (ATMS), that is needed to test new ramp-metering designs.

3) New ramp-metering schemes, such as System Wide Adaptive Ramp Metering (SWARM), have undergone testing and evaluation on I-210.

4) Caltrans District 7, which manages this freeway segment, continues to support researchers in exploring innovative traffic management techniques.

In our previous effort, microscopic [11] and macroscopic [12] traffic simulation tools has been calibrated to this test site.

VIII. RESULTS

The local traffic-responsive ramp-metering controller, without the queue length regulator, was first tested on the calibrated macroscopic cell transmission model (CTM) [12]. The desired mainline vehicle densities were obtained from an open-loop simulation of the CTM with a set of optimal time-of-the-day metering rates solved by the linear program in [9], [10]. Fig. 6 shows an example plot of the tracking of the mainline vehicle densities in the upstream and downstream cells (1 and 2 in Fig. 2) and the convergence of the ramp-metering rate. In the plot, the dashed lines are the desired densities or metering rate, and the solid lines are the actual quantities.

The traffic-responsive metering controller and the queue length regulator, together with the localized control strategy described in Section VI, were also tested in the calibrated macroscopic CTM simulator [12]. In addition to the regular traffic quantities that are measured by the loop detectors, this CTM simulator also provides the actual on-ramp queue...
lengths, which were used in the queue length regulator as the feedback. As a comparison, the optimal time-of-the-day metering plan was also simulated with the CTM simulator.

Some freeway performance measures in these simulations, as defined in Section II, are listed in Table I. In calculating the delays, the nominal free-flow speed $v_0$ is assumed to be 63 miles per hour.

In all simulations, the freeway segment served almost the same amount of demand, as measured by the Total Vehicle Distance $D_{V, tot}$. However, traffic-responsive ramp metering with localized strategy was able to reduce the congestion on the mainline and increase the Average Total Vehicle Speed $ar{v}_{V, tot}$ by almost 6%, while the optimal metering plan increased $ar{v}_{V, tot}$ by 5.3%. The Total Vehicle Delay $DL_{V, tot}$, which is the extra time spent due to the congestion, was reduced by 7.7% and 6.9% by the localized strategy and by the optimal metering plan, respectively, while the Total Vehicle Time $T_{V, tot}$ was reduced by 5.7% and 5.1% by these two metering strategies, respectively.

From these numbers, it can be seen that the localized metering strategy had even a slightly better performance than the optimal metering plan. This is partly due to the 5-minute time resolution of the optimal metering plan, which was chosen for the reason of computational efficiency.

### IX. Conclusions

In this paper, we presented a novel switching traffic-responsive ramp-metering controller that suits the different traffic dynamics under free-flow or congested conditions. The approach of multirate LQI was used to compensate for disturbances and accommodate the difference in the model sampling time and the metering rate updating time interval. In addition, a PI queue length regulator was also designed to limit the on-ramp queue within the storage capacity and to improve the performance of the currently used ad hoc “queue-override” scheme. A localized strategy was proposed to achieve the control goal of reducing the congestion’s spatial and temporal extension, using locally available information. Test results on the calibrated macroscopic traffic simulator demonstrated the performance and effectiveness of the switching ramp-metering controller, the queue length regulator, and the control strategy. The Total Vehicle Delay was reduced 7.7%, while the Total Vehicle Time was reduced by 5.7%.

### REFERENCES


