A Mathematical Programming Based Approach to Evaluate Ramp Metering Deployment Through Eclipse SUMO

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Abstract

In the study we summarize in this paper, we have sought the optimal number of ramp meters that are needed to be activated on a freeway segment using binary programming in conjunction with traffic simulation. In the microscopic simulation environment, a 10 km freeway stretch is designed with 9 on-ramps, which have varying traffic demands. For a given fixed signal scheme, at each cycle, the formulated optimization problem is solved using MATLAB in conjunction with the integration formed by Traci4Matlab, the solution set of which is further used by Eclipse SUMO to activate ramp meters. We have compared the performance of the algorithm we propose with the full-time ramp metering activation scenario, and the scenario with no control, in terms of density, travel time, and total throughput. Our findings as improvements show that the proposed algorithm can be used for adaptive ramp metering applications, and planning purposes as well.

1 Introduction

Traffic congestion becomes a major problem for developed cities. This problem drives us to find different solutions. The easiest solution can be increasing the capacity of the roadway however, the logical solution is to increase the effective use of capacity. Thus, nowadays the Intelligent Transportation Systems (ITS) have become an important field of study, because of their ability to provide solutions without major construction projects. However, ITS applications, as well, have construction costs, [1]. Therefore, from a planning aspect, the feasibility of realizing such tools should

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be considered [2]. The need for ITS applications can be identified by macroscopic traffic parameters, i.e., density, flow, and speed, however, these parameters cannot adequately help to decide the needed layout of ITS applications. In other words, controlling each of the segments or intersections of a freeway can provide worse or similar results in the case of controlling only the selected segments or intersections. Therefore, in our study, we have tried to find the points of traffic flow conflicts, which are better to be controlled with ramp metering (RM). In order to decide the conflict points, we have the problem using binary programming. Using the MATLAB, the solution to the optimization problem is obtained, which is further input to Eclipse SUMO via the provided connection by Traci4Matlab. For a defined fixed cycle of ramp meter, the solution helps to determine the conflict points to be controlled.

The rest of this paper is organized as follows. In Section 2, we have summarized the relevant literature. Section 3 introduces the methodology of this study combined with the optimization problem and the microscopic simulation environment. The results and discussion are given in Section 4. Finally, the main conclusions are presented in Section 5.

2 Literature Review

In the following brief review on the literature, we have presented the studies on the feasibility of ITS applications and ramp metering strategies.

In [2], a progressive plan to implement ITS applications is presented. It is seen that the field equipment need of ITS applications is not a minor problem to handle during the planning process, therefore it should be deeply analyzed to overcome future needs of the area. In [3], it is highlighted that several short-term solutions beside ITS applications can be adopted. Especially, the priority of the solutions with their potential benefits has to be considered for avoiding excessive cost.

In [3], in addition to the implementation analysis of ITS applications, the staff and driver acceptance of these applications are discussed with a survey. It is shown that after implementation of these ITS applications, staff with a belief in this technology is needed.

In this study, we have employed the RM as the controlling strategy, which is widely accepted and implemented as an ITS application for many years [1]. RM can be in an adaptive (responsive) fashion or it can be pre-timed (fixed-time). In [5], the results obtained from a well-known feedback controlling approach for RM, ALINEA is presented. The importance of [5] comes from presenting real-world results besides simulation results and, it presents clearly the improvements provided by RM in travel time and occupancy. In [6], the importance of the coordination between ramp meters on a freeway is highlighted, furthermore, it is pointed out that the coordination of ramp meters with urban traffic controllers to prevent excessive queue lengths has also to be considered. In [7], a comparison between local and coordinated RM strategies is presented. It is clear from the findings in [7] that both of them are highly effective. The major problem for realizing a coordinated RM strategy can be associated with the availability of of real-time traffic data or the communication failures. In [8], the pre-timed strategies are shown to be more effective on improving traffic flow conditions than adaptive strategies. Especially, the importance of having a solid data-collection plan is underlined.

The main contributions of our study can be divided into two aspects. Our approach can be used for planning purposes to decrease the amount of field equipment and, by that a step-wise transition from no-controlling to controlled freeway traffic flow under a limited budget is expected to be more feasible. Also, our algorithm can be used with both historic demand data and real-time traffic data, because it does not depend on precise measurements of consecutive detectors. In addition to that, our algorithm has a hybrid adaptive fashion in this study. The signal scheme is fixed in terms of green time and red time, but the activation time is adaptive dependent on the number of vehicles on the freeway corridor. Therefore, the algorithm has advantages in terms of both of the controlling approaches, i.e. adaptive and fixed-time.

3 Methodology

In the present study, we analyze a hypothetical road network with several on-ramps to decide the on-ramps that need to be controlled. First, we have formulated the optimization problem, which is presented in Section 3.1. Then, as presented in Section 3.2., we have conducted microscopic traffic simulations utilizing Eclipse SUMO and MATLAB in an integrated fashion.

3.1 Problem Formulation

To create the problem, let us consider a road segment, with a length of L km. Basically, the density of this road segment can be calculated by Eq. 1., where $\rho(t)$ represents the density at time t and $n(t)$ represents the number of vehicles on this road segment at time t.

$$\rho(t) = \frac{n(t)}{L} \tag{1}$$

If we consider the change in the number of vehicles only on the mainstream neglecting the ramps, we can write the equation as given in Eq. 2.

$$\rho(t+\Delta t) = \rho(t) + \frac{n_{in}(t+\Delta t) - n_{out}(t+\Delta t)}{L} \tag{2}$$

If there are $k \in K$ on-ramps connected to this road segment, we can write Eq. 2 as given in Eq. 3.

$$\rho(t+\Delta t) = \rho(t) + \frac{\sum_{k=1}^{K} n_k(t+\Delta t) + n_{in}(t+\Delta t) - n_{out}(t+\Delta t)}{L} \tag{3}$$

Let us consider that the control is provided only on on-ramps with RM. If we consider a fixed time RM with a cycle time of C, whose signal scheme consists of green time, g, and red time, r, then we can assume that RM can reduce the number of incoming vehicles by a rate of $\left(1 - \frac{r}{C}\right)$.

Therefore, we can write this equation by using the binary variable x_k, which is 0, if the $k'th$ ramp meter is off and is 1, if the $k'th$ ramp meter is on, as given is Eq. 4.

$$\rho(t+\Delta t) = \rho(t) + \frac{\sum_{k=1}^{K} n_k(t+\Delta t) - n_k(t+\Delta t) \cdot \frac{r}{C} \cdot x_k(t+\Delta t) + n_{in}(t+\Delta t) - n_{out}(t+\Delta t)}{L} \tag{4}$$

In order to operate the road segment in nearly optimal conditions, we aim to minimize the difference between a defined critical density,ρ_{cr}, and $\rho(t+\Delta t)$, at the end of each cycle, C, by using the Eq. 5.

$$\min \rho_{cr} - \rho(t) + \frac{\sum_{k=1}^{K} n_k(t+\Delta t) - n_k(t+\Delta t) \cdot \frac{r}{C} \cdot x_k(t+\Delta t) + n_{in}(t+\Delta t) - n_{out}(t+\Delta t)}{L} \tag{5}$$

Subject to

$$x_k \in (0,1) \tag{6}$$

$$\rho_{cr} - \rho(t) + \frac{\sum_{k=1}^{K} n_k(t+\Delta t) - n_k(t+\Delta t) \cdot \frac{r}{C} \cdot x_k(t+\Delta t) + n_{in}(t+\Delta t) - n_{out}(t+\Delta t)}{L} \geq 0 \quad (7)$$

First constraint given by Eq. 6 defines the decision variable x_k and, the second constraint given by Eq. 7 guarantees turning on the ramp meter, if it is necessary to reduce the number of incoming vehicles. If there is no optimal solution for Eq. 5, then all the ramp meters will be turned on.

3.2 Simulation Setup

We have used MATLAB to create the problem given in Eq. 5 and, in order to provide the interaction with Eclipse SUMO [9], we have used Traci4Matlab, which is an implementation of TraCI [10]. At each time step, MATLAB gathers the number of vehicles on the road segment and on the ramps from Eclipse SUMO, and processes to find which of the ramp meters should be turned on. Then, MATLAB provides this solution set to Eclipse SUMO.

To test our algorithm, we have designed a roadway with a length of 10 km, composed of 20 links. There are 9 on-ramps connecting to the mainstream at each kilometer with an acceleration lane. Each of the acceleration lanes has a length of 350 meters. Mainline has 2 lanes and a speed limit of 100 km/h. The same speed limit is provided for on-ramps, as well. The test network is presented in Fig. 1.

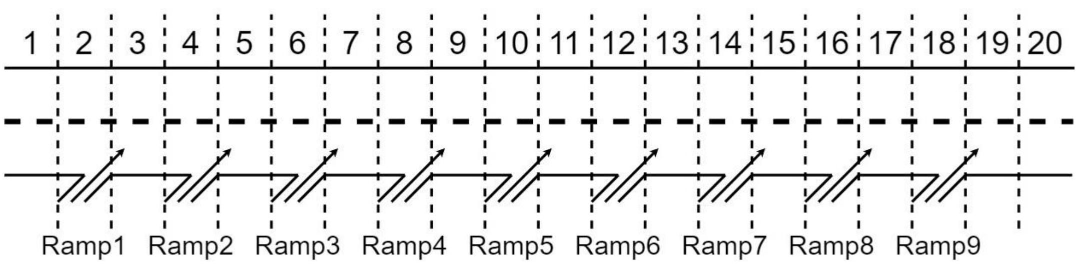

Figure 1: The sketch of the test network

To analyze the effect of different traffic demands coming from on-ramps, we have defined four different demand functions for on-ramps, as presented in Fig. 2, where the mainstream demand is 1600 veh/h.

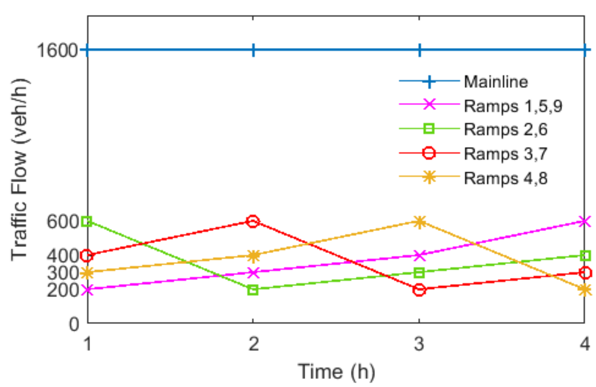

Figure 2: Demand profiles of mainline and on-ramps

As shown in Fig. 2, the demand functions of on-ramps give the same values, but for different time intervals. To model the longitudinal movement of vehicles, we have used Krauss car-following model and, for the lateral movement, we have used LC2013 model. To obtain a more realistic lane distribution of vehicles in congested traffic conditions, we had to increase the number of lane changes. Therefore, a parameter of LC2013 model is set to a different value from its default value. The maximum acceleration and deceleration are set to 3.5 m/sec^2, the maximum speed is set to 27.5 m/sec, the desired time gap is set to 2 sec and the minimum spacing is set to 1 m. To have a more realistic speed distribution of vehicles, the imperfection parameter of Krauss car-following model is set to 0.5. The only parameter differed from its default value of lane-change model is LCAssertive and, it is set to 4. By this way, lane changing maneuver becomes easier for vehicles. Furthermore, it does not cause any accidents.

We have designed three scenarios, i.e., partial RM, full-time RM, and no RM. In the first scenario, at the end of each cycle, our algorithm turns on the needed ramp meters for the next cycle, and turns off the others. In the second scenario, each ramp meter is turned on for the whole simulation duration. In the third scenario, there is no ramp meter at on-ramps. After several trials, we have decided to set the cycle length, red time, and green time, respectively to 15 seconds, 10 seconds, and 5 seconds. The simulation time step is chosen to be 0.1 sec and, the total duration of the simulation has been set to 14400 sec. The first half an hour of the simulations is considered as the warm-up duration. Therefore, we have presented the results measured for 210 minutes.

4 Results and Discussion

We have compared three scenarios, in terms of density measurements at each road segment, the variation of travel time, and the total throughput of the system. Density values are presented to show, which road segments are congested, and which control scheme has the best effect on the road network. Variation of travel time can provide us an insight about the ability of control schemes on organizing traffic flow. Total throughput is important as well, because lower density values can cause a reduction in the total throughput of the system. Therefore, the total throughput of the system can show whether the control scheme limits the traffic flow or it provides near-optimal conditions.

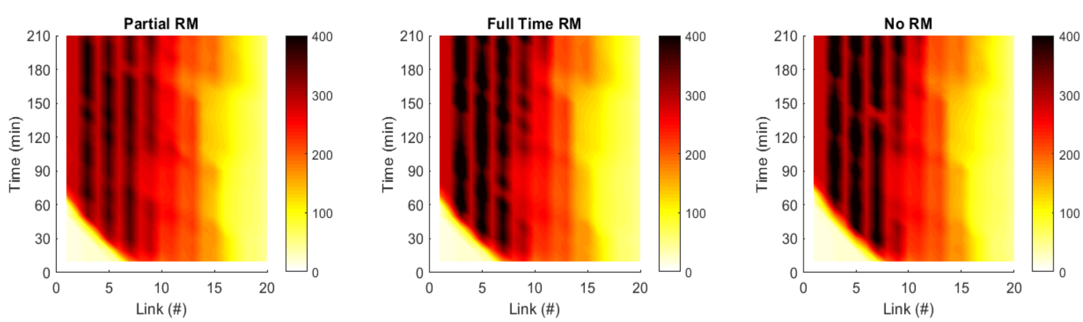

Figure 3: Density measurements over the network for the scenarios

In Fig. 3, density measurements retrieved on links are presented. For the given car-following parameters and length of vehicles, maximum density on a single lane is 200 veh/km, and since the mainline has two lanes, the maximum density is limited by 400 veh/km. It is shown that the congested links are similar for each scenario, however, in case of Partial RM application, the severity of congestion is reduced. In addition, the length of the congested area is reduced. Although such improvements are obtained, after the 10th link, the differences in density values cannot be identified. Therefore, the travel time is analyzed as well.

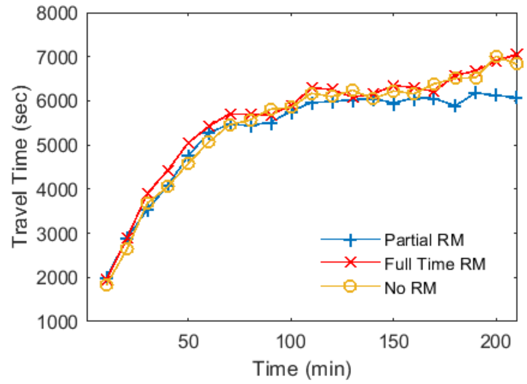

Figure 4: Change of travel time for the scenarios

As shown in Fig. 4, travel time becomes reduced by time for the case of the Partial RM application. It shows as well that the application of RM for the entire simulation period can have an adverse effect. It should be noted that the ramps have variable demands with identical upper and lower limits, therefore the results we have obtained are valid in cases of the type of demand functions and hypothetical road network we have considered. In other words, rather than criticizing the effectiveness of the RM application under our hypothetical setups, it is better to make use of our approach in comparative evaluations.

In order to further compare the organizing effect of our algorithm with other scenarios, the variation of the travel times is presented in Fig. 5.

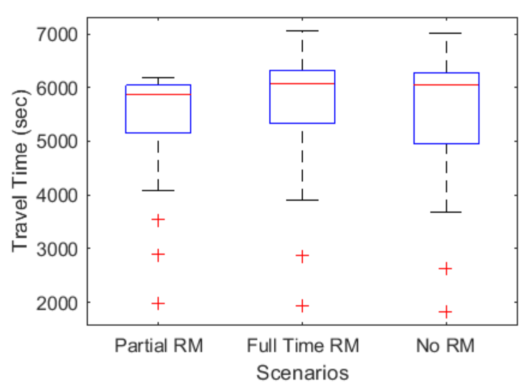

Figure 5: The variation of travel times for the scenarios

As shown in Fig. 5, the smallest mean travel time is provided as a result of having applied our algorithm. Also, the variation in travel time is limited. It shows that our algorithm can provide a more predictable and acceptable travel time for drivers. However, our improvements would have reduced the total throughput of the system. Therefore, in Fig. 6, the variation of the total throughput of the system is presented.

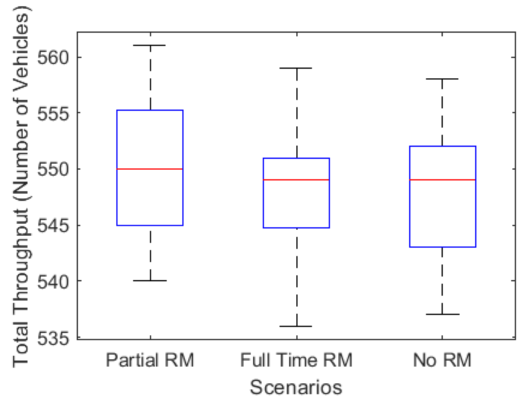

Figure 6: The variation of total throughput for the scenarios

As presented in Fig. 6, our algorithm can provide the smallest mean travel time, while serving more vehicles than the other cases. Although the improvement is not major, it should be noted that the hypothetical network has no off-ramps, therefore congestion is inevitable. Dependent on our findings, we can assert that the algorithm we propose is worth using with a real network and real traffic demands. Furthermore, to discuss the most active ramp meters, we present the number of activations of ramp meters in Fig. 7.

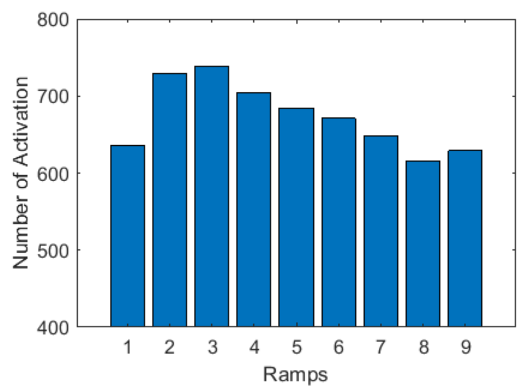

Figure 7: The number of activations of the ramp meters

Fig. 7 shows us that the need for RM application for on-ramp varies with traffic demands and traffic conditions on road segments. Therefore, we point out that our algorithm can provide the hourly ramp metering scheme off-line for given traffic demands or can provide it adaptively in real-time. The off-line application can be used to find near-optimal layout for ramp meter constructions. In the adaptive case, as presented in this study, it can provide better traffic conditions than a full-time RM application or no RM application.

5 Conclusion and Future Research

In this study, we have handled a hypothetical freeway road stretch with a length of 10 km and 9 on-ramps to find the optimal activation order of ramp meters. To find the needed ramp meters, we have utilized binary programming. With the integration between Eclipse SUMO and MATLAB, at each predefined signal cycle, the solution set of the activated ramp meters has been used by Eclipse SUMO. The proposed algorithm can be useful for finding the near optimal activation order of a given layout of ramp meters adaptively and also can be used to find the near-optimal layout for a roadway stretch with no ramp meters. In other words, to decrease the cost of freeway control project, by using this algorithm, we can find necessary ramp meters that should be constructed earlier. In this study, we have applied the algorithm we have proposed in an adaptive fashion and presented the activation number of ramp meters to argue that controlling each on-ramp full-time can be unnecessary to provide better traffic flow conditions. In summary, having employed our algorithm has returned better results in terms of density, travel time, and total throughput than full-time control and no control.

In our future research, we want to improve this algorithm with adaptive green time for given cycle length. In this manner, we will find the optimal order and optimal green time at each cycle. Furthermore, a real-world network from Istanbul, Turkey with no RM application will be handled to find the optimal layout to decrease the cost of construction projects. Therefore, this study will be extended to increase the adaptability of the system we have designed and test its usefulness for planning purposes.

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