Effect of Distance between Ramp and Upstream Signal on Ramp Meter Operation

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Abstract

Ramp metering is typically proposed as a responsive strategy that takes freeway traffic parameters as control inputs to the ramp control logic. Such a strategy can be implemented in two ways: isolated ramp control or coordinated ramp control. Coordinated ramp control typically involves the cooperation between several ramp meters connected to a freeway segment to manage traffic on the freeway and traffic all ramps. Few studies also proposed the coordination between the on-ramp and the upstream traffic signal. Such coordination can help to mitigate congestion on the freeway and to avoid queue formation at the on-ramp. In this study, previous work on ramp metering and upstream signal coordination was extended to further evaluate the performance of such schemes by considering the impact of the distance between the upstream traffic signal and freeway. Extensive simulations in SUMO were performed to evaluate the benefit of the proposed coordinated strategy and the impact of ramp distance on the effectiveness of such coordination.

Keywords: Ramp meter, freeway, upstream traffic signal, SUMO, queue length, travel time

1. Introduction

Ramp metering is a ramp management strategy to control the number of vehicles entering a freeway using a traffic signal [1-3]. Ramp meters are programmed with much shorter cycle time in order to allow a single vehicle or a very small platoon of vehicles (usually two or three) per green phase. The metering rate is based on several traffic parameters (e.g., volume, occupancy, density, speed, etc.) on the freeway. The goal of ramp metering is to increase throughput, speed, and to balance the demand and capacity of the freeway segment to maintain the optimum operation of the freeway [4]. However, while deploying ramp metering, it is crucial to consider the queue formation and effective queue discharge strategy so that the ramp demand does not exceed the capacity. Ramp metering can be generally categorized into two types. First, local or isolated ramp metering schemes in which the ramp signal is controlled independently of other ramps connected to the freeway using a fixed or dynamic control logic. The locally controlled metering scheme can be fixed logic [5] or adaptive (traffic responsive) [6-9]. Secondly, coordinated ramp metering, in which the ramp signal is connected to other ramps connected to the freeway [10-14].

The two strategies are used to mitigate congestion on the freeways. However, in many cases, the on-ramp is used to connect an arterial with a freeway. In this case, if there is a traffic signal on the arterial close to the on-ramp, the on-ramp traffic is highly affected by the state of the upstream signal. With insufficient ramp storage, ramp queue may spillback to the upstream signal and affect the operations of the surface street system as well as a ramp. [15] Authors in [16] suggest suspending ramp metering to flush the queue when spillover occurs. However, such override will reduce the intended benefit of ramp metering. Hence, it would be significant to use the information of the upstream traffic signal on the arterial in the ramp meter configuration. This kind of feedback from the upstream signal and the ramp would relieve the ramp traffic before it leads to congestion and improves ramp operations [17, 18].

In this study, a special case of ramp metering is discussed where the on-ramp has limited storage. If the ramp meter is operated with a restrictive metering rate, it will form long queues on the ramp that eventually exceeds the ramp storage, and the queue will stretch back to the arterial segment. On the contrary, if the metering rate is kept long, this results in a negative impact on the freeway. The longer green phase on the ramp meter will behave like an uncontrolled ramp, and consequently, the logical benefit of ramp metering will not be achieved. Hence, it is proposed that the ramp meter should be able to avoid queue formation by increasing the metering rate when the flow entering the ramp is increased. To avoid queue formation, the ramp meter should be able to acquire phase information of the upstream traffic signal. The proposed

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scheme uses a basic level of coordination where the green interval of the ramp meter is increased based on the current phase of the traffic signal to allow or restrict traffic on-ramp. The upstream signal is implemented with fixed control logic, whereas the ramp meter can dynamically adjust its green phase according to the upstream traffic signal. The ramp meter dynamically changes the traffic program according to the current phase of the traffic signal. For each phase of the traffic signal, a ramp meter program was defined. However, when the ramp meter detects the phase change at the upstream traffic signal, it does not immediately switch to the new program, but rather wait for a particular period of time in order the vehicles passing through the intersection in the new phase can reach the ramp exit (or freeway entry). An alternative approach will be the use of vehicle detectors to detect the arrival of vehicles from a particular approach. However, this approach is subject to estimation errors as the vehicles passed in the previous phase might arrive late.

The coordinated operation of ramp meter and the upstream signal can bring potential improvement in ramp operation to efficiently discharge the ramp queue with a lesser impact on the freeway operation [19-22]. However, such coordination is likely to be impacted by several parameters of traffic and the traffic signal. For instance, the distance between the ramp meter and the upstream signal is an important parameter that can impact the potential benefit of the coordination. It is expected that over larger distances, the traffic behavior may change, particularly during the lane changing and entry to the ramp, the vehicles may experience some delays, and the travel time can significantly vary. Despite the possible impact of such expected behavior, there is a lack of attention in the literature to investigate the impact of distance on ramp-upstream coordination schemes. Knowing the significance of the problem, this study is an extension of the authors’ previous work to investigate the impact of distance between the ramp meter and the upstream signal [19].

This study proposes a simpler and easy to implement a coordination scheme between an upstream traffic signal and a freeway ramp meter. The benefit of such coordination is tested using accurate simulations. The study also evaluates the impact of distance between the upstream traffic signal and the ramp meter on the overall system performance, particularly the impact of upstream signal to ramp meter distance on the ramp queue length, ramp waiting time, and freeway travel time.

2. Related Works

Traffic responsive ramp metering has been proven to be an effective method for traffic management on freeways [3], which can discharge the traffic flows and prevent congestion from propagating over the freeway. One of the most commonly used ramp metering strategies is known as ALINEA [6, 7]. The algorithm considers freeway occupancy as input and computes the metering rate as a control variable that varies in response to changes in occupancy. ALINEA uses a single detector per lane of the freeway installed downstream at a distance of 40 meters or 400 meters. The downstream detectors measure the occupancy rate and send it to the controller at regular intervals, usually 40 seconds. The controller computes the difference between the desired occupancy threshold and measured occupancy and determines the metering rate for the next interval (40 seconds). ALINEA has been widely investigated in numerous studies [23-26]. However, ALINEA is a local metering scheme, which only considers the occupancy on the freeway to control the metering rate. Furthermore, the performance of ALINEA greatly depends upon the optimum selection of the congestion threshold [27].

ALINEA has been extended to work in coordinated system-wide metering in the METALINE algorithm [28]. The METALINE algorithm computes the metering rate using the list of occupancy values from several detectors on different ramps. The algorithm is similar to ALINEA in its response to the difference in the occupancy in two successive time intervals making it more sensitive to traffic variations. The disadvantage of METALINE is the complex calibration of the algorithm for multiple ramps. Apart from ALINEA, several local [5, 8, 9, 24], coordinated [4, 10-12, 14, 17] and hybrid [29-32] ramp metering schemes proposed in the literature. The aforementioned ramp metering techniques (either local or coordinated) are designed to implement considering freeway and ramp traffic only.

Only fewer works are related to coordination between arterial and ramp. Historically, freeways and arterials are controlled and managed separately [33, 34]. Aydos et al. [35] show that integrated operation management of freeways and arterial traffic can bring network-wide net improvements. Dabiri and Kulcsár [21] proposed a strategy that considers both and upstream traffic parameters to configure ramp meters to achieve system-wide performance goals. Landman et al. [22] proposed that the coordination between upstream intersection and freeway can significantly improve the overall performance of the network; however, the authors did not provide any evaluation of such operations. A closely related study on the coordination of upstream arterial signal and ramp meter is presented in [20].

However, the study proposes a complex control algorithm that takes inputs from upstream traffic signal and ramp, and it becomes difficult to identify whether the achieved performance gain is due to the coordination between the ramp meter and upstream signal or due to other network parameters. Furthermore, the study considers low vehicle densities, and it does not specify all the simulation parameters (e.g., traffic volumes, traffic signal cycle time, etc.), which makes it difficult to evaluate the potential performance gain.

In Shaaban et al. [19], a simpler coordination scheme was proposed in which the ramp meter received the phase information from the upstream signal in real-time and adjusted its green phase accordingly to allow or restrict the vehicles to enter the freeway. However, the work does not investigate the impact of distance on the performance of such coordination. In Yang et al. [36], the authors investigated the impact of ramp queue length on the traffic operations. However, the study aims at the optimal queue length design rather than ramp meter design.

3. System Model

In this study, a scenario of a 3-lane freeway connected with an arterial road through an on-ramp was considered. The ramp connects the traffic from an upstream 4-arm intersection with a traffic signal. The scenario is illustrated in Fig. 1.
The upstream signal is connected to the ramp meter, such that the ramp signal can read all the parameters (current phase, phase duration, next phase, etc.) of the upstream signal in real-time. In this study, the upstream signal has been configured with four phases, where each phase controls the traffic for a single arm at a time. The four phases are depicted in Fig. 2.

Table 1. Upstream Traffic Signal Parameters

<table>
<thead>
<tr>
<th>Signal Phase</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>40</td>
</tr>
<tr>
<td>Phase 2</td>
<td>30</td>
</tr>
<tr>
<td>Phase 3</td>
<td>40</td>
</tr>
<tr>
<td>Phase 4</td>
<td>30</td>
</tr>
</tbody>
</table>

3.1. Non-Coordinated (Fixed) Control
The network was first studied using simulation with the original fixed cycle to see the pattern of queue formation. The ramp meter was configured with a fixed cycle length of 10 seconds (3 seconds green, 2 seconds yellow, and 5 seconds red).

3.2. Coordinated Control
To implement the coordinated control between the upstream signal and ramp meter, the queue formation pattern was further analyzed. Multiple simulations were performed using four different traffic counts at each of the four phases of the traffic signals and analyzed how the queue length increases during each phase of the upstream signal. The ramp meter is configured to automatically increase or decrease the green phase. Four different ramp meter programs are defined to be used during the specific phase of the upstream signal. These ramp meter programs are given in Table 2 and are very similar to [16].

If the ramp meter is configured with a very small green phase to restrict vehicles to enter the freeway, or if more vehicles are coming from the upstream intersection to enter the ramp as compared to the vehicles leaving the ramp, the queue on the ramp will increase and can lead to congestion or jam on the upstream arterial. To avoid this situation, an occupancy detector is installed close to the ramp entry on the arterial side. Thus, if the occupancy detector is actuated, it shall activate the green phase for a period to allow enough vehicles to free the ramp queue. A value of 30 seconds was used for such a situation.

Table 2. Ramp Meter Programs

<table>
<thead>
<tr>
<th>Program ID</th>
<th>Phase Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Y</td>
</tr>
<tr>
<td>Meter 1</td>
<td>2</td>
</tr>
<tr>
<td>Meter 2</td>
<td>3</td>
</tr>
<tr>
<td>Meter 3</td>
<td>6</td>
</tr>
<tr>
<td>Meter 4</td>
<td>4</td>
</tr>
</tbody>
</table>

4. Simulations
Several microscopic simulation packages are used in traffic studies. These packages include Eclipse SUMO (Simulation of Urban Mobility) [37], CORSIM [38], Paramics [39], SimTraffic [40], and VISSIM [41, 42]. They can be used in modeling different types of networks with a different variety of geometry and traffic characteristics. These packages provide a reliable technique for a detailed analysis of different scenarios and strategies for traffic operations studies, including unsignalized intersections [41, 43, 44], signalized intersections [45-47], and roundabouts [48-50]. In this study, SUMO was used to investigate the case study. The traffic flow rates are selected according to Table 3.

Table 3. Traffic Flow Parameters

<table>
<thead>
<tr>
<th>Link</th>
<th>Lanes</th>
<th>Flow Rate (vph)</th>
<th>Vehicles Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway</td>
<td>3</td>
<td>3600</td>
<td>Bus, car, truck</td>
</tr>
<tr>
<td>Westbound</td>
<td>3</td>
<td>3600</td>
<td>Bus, car, truck</td>
</tr>
<tr>
<td>Arterial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northbound</td>
<td>2</td>
<td>2600</td>
<td>Bus, car, truck</td>
</tr>
<tr>
<td>Southbound</td>
<td>2</td>
<td>1800</td>
<td>Bus, car, truck</td>
</tr>
<tr>
<td>Eastbound</td>
<td>2</td>
<td>1800</td>
<td>Bus, car, truck</td>
</tr>
<tr>
<td>Westbound</td>
<td>2</td>
<td>1800</td>
<td>Bus, car, truck</td>
</tr>
</tbody>
</table>
5. Results and Discussion

The simulation results produced with non-coordinated (fixed time) control are compared with coordinated control (ramp meter and upstream signal) logic. The coordinated control logic outperforms in terms of ramp queue discharge, travel time, and delay. The ramp queues were eliminated in time less than 30 seconds. Two metrics were used for evaluating the proposed approach: travel time and delay. Travel time and delay are the two most commonly used metrics for evaluating the performance of roadways. The metrics are being used in a plethora of traffic studies as these metrics provide a direct indication of the vehicle speed and the overall system performance.

5.1. Queue Length

Queue length is calculated as the length in meters from the junction (ramp meter in this scenario) until the final vehicle in line. The queue length is investigated in the given scenario for both coordinated and non-coordinated scenarios, and the result is depicted in Fig. 4.
investigated using three different ramp lengths (500 m, 1000 m, and 1500 m). The results are depicted in Fig. 5.

Fig. 5. Queue Length (m) over the ramp

The results showed that the coordinated metering strategy is efficient for all the three ramp lengths. However, the relative benefit in terms of queue length control seems more for smaller ramp length. One possible reason for this behavior is that the long distance between the intersection and ramp meter reduces the synchronization as the vehicles may arrive late.

5.2 Waiting Time
Waiting Time is defined as extra time spent by drivers against their expectations. In SUMO, it is calculated as the number of seconds a vehicle has a speed of less than 0.1 m/s. Waiting time typically increases due to several reasons such as the delay due to slow vehicle speed, frequent vehicles stopping, deceleration while approaching the intersection, etc. The average waiting time for all vehicles over ramp is evaluated in Fig. 6.

The delay experienced by ramp traffic was significantly reduced in all three scenarios. However, the relative reduction in the waiting time is greater for longer ramp length (1500 m). The analysis shows that the average waiting time over the ramp is reduced by almost 3 times for 500 m, 2.5 times for 1000 m, and 2.4 times for 1500 m length of the ramp.

Fig. 6. Average waiting time of all vehicles on the ramp

5.3 Travel Time
Travel time is the elapsed time it takes for a vehicle to traverse a given segment of a road. The ramp queue can always be discharged at the cost of a reduction in the travel time of the freeway. It is, therefore, important to investigate the travel time of the freeway when proposing any ramp metering strategy. In the proposed coordinated strategy, the travel time results are evaluated, as depicted in Fig. 7.

The average travel time for all vehicles on the freeway is evaluated for different ramp lengths using both coordinated and fixed metering strategies.

Fig. 7. Average travel time of all vehicles on the freeway

It can be observed that the proposed metering strategy has a minimal impact on the travel time on the freeway.

6. Conclusion
In this paper, a simple yet effective coordination scheme between a ramp meter and the upstream traffic signal was proposed. It is argued that such a coordination scheme can be impacted by the distance between the ramp and upstream signal, and hence the proposed coordination scheme is evaluated for various distances (500 m, 1000 m, and 1500 m) to measure the impact on the overall road network operations. The simulation results showed that the distance had a clear impact on the ramp queue discharge, and it is reported that the coordination is more effective for smaller distances between the ramp and the upstream signal in terms of queue length and average waiting time of vehicles. In addition to the ramp operation, the impact of distance over freeway traffic is relatively smaller using the coordinated operation. The coordinated operation of ramp meter and upstream signal over large ramp lengths can be further improved if the traffic leaving in each phase of the upstream signal and the travel time to reach the ramp is accurately predicted. As future work, coordination using reinforcement learning to control the ramp meter should be studied.

References


