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Queue Discharge at Freeway On-Ramps Using Coordinated Operation of a Ramp Meter and an Upstream Traffic Signal

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Abstract

Ramp metering is an effective way of maintaining optimum traffic conditions and mitigating congestion on freeways. Several strategies for ramp metering exist in the literature. They are typically based on the freeway traffic parameters as control inputs to the ramp control logic. The ramp signal can be controlled in two ways, i.e., locally controlled (isolated ramp control) and coordinated ramp control. Coordinated ramp control refers to the ramp metering strategies in which several ramp meters connected to the freeway segment are dynamically controlled by considering traffic flows along all ramps. Coordinated ramp metering can play a vital role in freeway congestion mitigation on the ramps as well as normalize the traffic flow over the freeway. In this study, an alternate coordinated metering scheme that uses the state of the upstream traffic signal on arterial as the control input to the ramp meter is proposed. The proposed method aims to prevent long queues on the ramp with limited storage by taking feedback from the upstream traffic signal on the arterial, especially when the ramp has a small storage area for vehicles. Simulation results show a significant reduction in the queue length over the ramp using the proposed scheme. Additionally, the proposed scheme also benefits the arterial traffic.

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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 aforementioned 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. 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 [15, 16].

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 traffic parameters and phase information of the upstream traffic signal. The proposed 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.

2. Literature Review

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 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 [2, 17-20]. 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 [21]. ALINEA has been extended to work in coordinated system-wide metering in the METALINE algorithm [22]. 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, a number of local [5, 8, 9, 18], coordinated [4, 10-12, 14, 15] and hybrid [23-26] 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 related to coordination between arterial and ramp. Historically, freeways and arterials are controlled and managed separately [27, 28]. Aydos et al. [29] show that integrated operation management of freeways and arterial traffic can bring network-wide net improvements.

Dabiri and Kulcsár [30] proposed a strategy that considers both and upstream traffic parameters to configure ramp meters to achieve system-wide performance goals. Landman et al. [31] 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 [32]. 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 make it difficult to evaluate the potential performance gain.

3. Simulation Study

Several microscopic simulation packages are used in traffic studies. These packages include CORSIM, Paramics, SimTraffic, and VISSIM [33-37]. 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 [38-40], signalized intersections [41-43], and roundabouts [44-46]. In this study, VISSIM was used to investigate the case study [47]. The case study included a road network consisting of a freeway, a single-lane ramp with ramp meter, and an arterial roadway with a signalized intersection is shown in Figure 1. The length of the ramp is 150 m. The upstream signal has a fixed cycle length of 160 seconds with four phases.

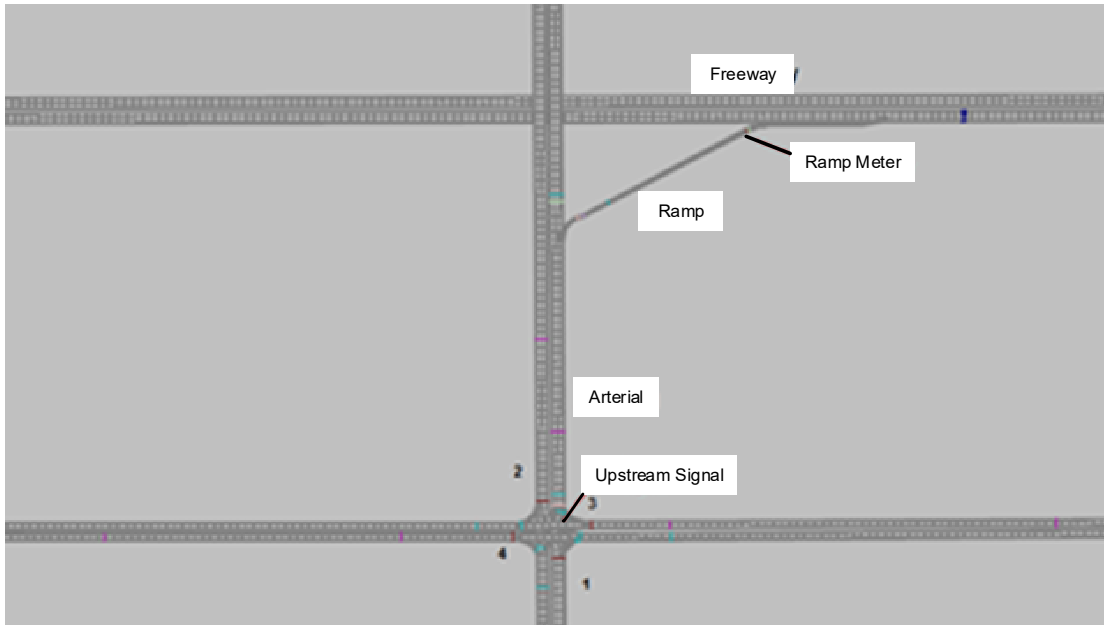


Figure 1: Case Study of Ramp with an Upstream Traffic Signal.

The traffic flow rates are selected according to Table 1, whereas the signal control timings of arterial and ramp are given in Table 2.

Table 1: Flow Rates (vph) Used in the Simulation.

SN	Link	Flow Rate (vph)	Vehicle Composition
1	Freeway-EB	3600	Default
2	Freeway-WB	3600	Default
3	Arterial-NB	2600	Default
4	Arterial-SB	2600	Default
5	Arterial-WB	1800	Default
6	Arterial-EB	1800	Default

Table 2: Signal and Ramp Timings.

Upstream Arterial Traffic Signal	Downstream Freeway Ramp Meter
Cycle length	160 seconds
Phase 1	50 seconds
Phase 2	50 seconds
Phase 3	30 seconds
Phase 4	30 seconds
Cycle length	8 seconds
Green Interval	2 seconds
Yellow Interval	2 seconds
Red Interval	4 seconds

3.1. 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 8 seconds (2 seconds green, 2 seconds yellow, and 4 seconds red). Figure 2 shows the formation of the queue on the ramp. It can be observed that the queue length increases at some time and then drops. The increase of the queue length results from the heavy traffic generated by the upstream signal.

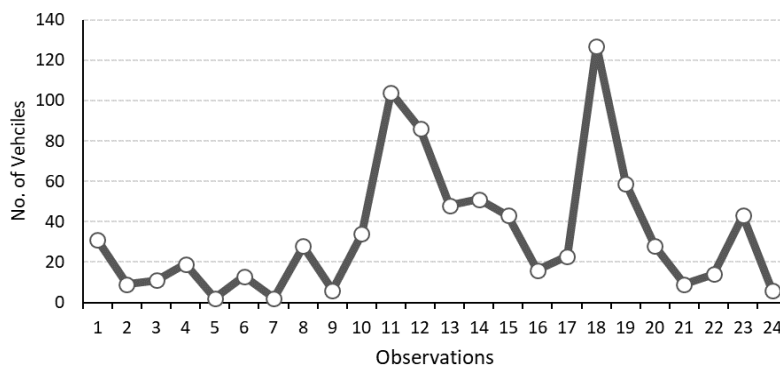


Figure 2: Queue Length study of the ramp.

3.2. Coordinated Control

To implement the coordinated control between the upstream signal and the 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. To implement the proposed scheme, it is crucial that the ramp meter is constantly updated by the upstream signal about the running phase and phase changes in real-time. The traffic signal phases are configured according to Table 3.

Table 3: Cycle Split based on Coordinated Logic.

Upstream Signal Phase	Ramp Meter Cycle	Green Interval	Amber Interval	Red Interval
1	8	4	2	2
2	8	2	2	4
3	8	2	2	4
4	8	3	2	3

4. 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, i.e. 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.

4.1. Travel Time

Travel time is the elapsed time it takes for a vehicle to traverse a given segment of a road. The travel time results are depicted in Figure 3. As depicted in Figure 3, the travel time is largely reduced on the ramp without any impact on the arterial. The total travel time for all vehicles is reduced by one third. At the same time, the travel time on the arterial is also slightly reduced by 18% as compared to the non-coordinated approach.

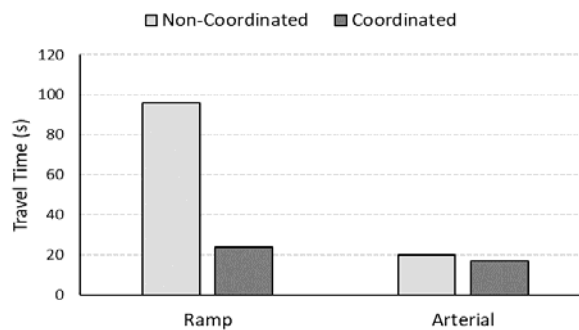


Figure 3: Travel Time Comparison.

4.2. Average Delay

Delay is defined as extra time spent by drivers against their expectations. Delay can typically occur due to several reasons such as the delay due to slow vehicle speed, frequent vehicles stopping, deceleration while approaching the intersection, etc. The average delay for all vehicles over ramp and arterial is evaluated in Figure 4. The delay experienced by ramp traffic was significantly reduced with a slight decrease in the arterial traffic. The analysis shows that the average delay over the ramp is reduced by a factor of 25%, whereas a light reduction in delay over the arterial section was also observed.

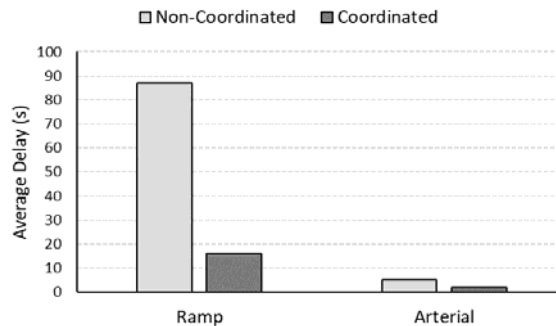


Figure 4: Delay Comparison.

The study provides a preliminary understanding of the proposed method. As future work, the integration of the upstream signal with ramp meter running ALINEA [6] local metering algorithm will be implemented to investigate possible improvements in the ALINEA algorithm and the impact on the freeway congestion. Although the scenario only includes arterial traffic entering the ramp, however in practice, there might be other minor streets or service roads that feed the given on-ramp more vehicles that must be discharged before the arterial signal turns the phase that provides maximum demand to the ramp.

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