Connected Vehicles Sensing Approach for Improving Freeway Operation with Ramp Metering Control

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ABSTRACT

Responsive ramp metering operates in adjusting on-ramp flow to enter the mainline freeway, dependent upon the detected congestion level of the mainline freeway. This technique theoretically sounds to alleviate recurring and non-recurring congestions, but greatly relies on prompt on-ramp and mainline freeway traffic detections of speed and flow variations. However, the traditional fixed detectors are a barrier to achieving the designated goal because of their incapability of quickly capturing the spatiotemporal patterns of congestion. With the emerging connected vehicle (CV) and/or autonomous vehicle (AV) technology (or CAV), it potentially provides a solution to the addressed problem trough make the CAV vehicles "floating sensors" that seamlessly cover the concerned highway over continuous time horizon. As a cost-effective, risk-free approach to quantitatively capture the CAV-affected driver behaviors, the developed method is to explore the synthesis on the operation of ramp meters at a real-world freeway facility with CAV support. The simulation results suggest positive benefits of improving freeway operation with ramp metering facility in CAV environment.

1. BACKGFROUND

The Connected Vehicle (CV) technology expects to enable the exchange of safety and operational information among road users and infrastructures via the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The V2I communication could make CVs become a kind of "floating sensors" that seamlessly cover the concerned highway region over continuous time horizon. With such a floating sensing ability, we may adapt it into the control systems such as ramp metering system at freeway facilities to make the meting controller capable of timely identifying the traffic conditions of the mainline freeway and the on-ramp, and the upstream intersection that connects the on-ramp. It then becomes passible for the controller to timely adjust the ramp flow rate entering the freeway for reducing the on-ramp traffic disturbance to the mainline freeway traffic while reducing the possibility of spillbacks from the on-ramp. In this way, the ramp metering controller could better capture the accurate traffic situation on both mainline freeway and ramps so that an optimum ramp rate could be determined in a real-time manner. This is the optimum synthesis we assume to achieve via using the "floating sensor" data with the support of V2I function.

To conduct a proof-of-concept study with a cost-effective and risk-free approach, a simulation-based testbed is developed to explore the synthesis on the operation of ramp meters at a real-world freeway facility within the envisioned CV environment. All affected driver behaviors are identified from the literature review, and then they are incorporated into the Human Driver Model (HDM) and the Intelligent Driver Model (IDM) in the VISSIM environment [1,2,3]. The interactions between the CV-affected driving behaviors and measures of effectiveness (MOE) are associated by the aggregated effect measures. To this end, this research will formulate an integrated ramp metering control algorithms, using real-time traffic measurements via the CV technology in the simulation environment. Multiple priority objectives are explicitly set up to delay the congestion due to internal perturbations, to maintain the throughput of freeway while preventing on-ramp vehicles from overflowing into arterials.

2. METHODOLOGY

3.1 CV-Affected Behavior Factors

An in-depth literature review [4,5] suggests that the CV-affected behavior factors include: perception-reaction time (RPT), desire speed (DS), estimation errors on spacing and relative speed, spatial anticipation, desired distance in the car-following state, and lane-changing desire [3,6,7,8] .

To quantify the aggregated influence of the CV-affected driver behaviors on traffic flow dynamics, the Integrated Dynamic Model (IDM) [9], has been selected to reflect the CV impacts on traffic operation by measuring changes of RPT, desired headway (DH) and DS. The IDM has the capability of representing various congestion patterns consistent with realistic traffic flows. These features of the IDM make it suitable for analyzing the traffic dynamics in the CV environment at a freeway facility. In the IDM, the vehicle acceleration is expressed as:

$$\dot{v} = a\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*(v,\Delta v)}{s}\right)^{2}\right] \quad (1)$$

where, v is the subject vehicle's speed; s is the following distance, and Δv is the following vehicles' relative speed to the leading vehicle. This model consists of a free acceleration component $a\left[1 - \left(\frac{v}{v_0}\right)^{\delta}\right]$ and a braking interaction component $-a\left(\frac{s^*}{s}\right)^{2}$. The free acceleration component yields an acceleration slightly smaller than the maximum acceleration a as the driver approaches the desired speed v_0.

In the braking interaction component, the actual space gap s is compared with the desired distance s*, which can be expressed as:

$$s^*(v, \Delta v) = s_0 + max(0, vT + \frac{v\Delta v}{2\sqrt{ab}}) \quad (2)$$

which is the sum of the minimum spacing at standing traffic s_0, the velocity-dependent safety distance vT corresponding to the desired time headway T and a dynamic part $\frac{(v\Delta v)}{(2\sqrt{ab})}$. The dynamic part implements an accident-free 'intelligent' braking strategy that limits the braking deceleration to the comfortable deceleration b in nearly all situations. Considering the CV-affected behaviors, the acceleration α is given by:

$$\dot{v}(t + \tau_i) = a \cdot \{1 - \left[\frac{v(t+\tau_i)}{v_0}\right]^{\delta} - \left[\frac{s^*(v(t+\tau_i), \Delta v(t))}{s(t)}\right]^{\delta}\} \quad (3)$$

$$s^*(v, \Delta v) = s_0 + max(0, \square \cdot vT + \frac{v\Delta v}{2\sqrt{ab}}) \quad (4)$$

A lane-changing model developed based on the Hidas lane-changing model [1,7] is adopted to depict the effect of the CV on the lane-changing desire. The greatest advantage of the Hidas model is that it contains functions to reflect the cooperative and forced lane change behaviors and relaxation phenomenon, which are often observed in congested freeway bottleneck facilities, but less modeled in many other lane-changing models. The modified IDM and Hidas models upon applying the CV-affected behaviors are presented in the remaining part of this subsection.

3.2 Multi-Objectives of Integrated Adaptive Ramp Metering System

To formulate the integrated adaptive ramp metering control algorithm by using real-time traffic measurements, multiple priority objectives are developed to improve the systematic performance and to delay the mainline freeway breakdown. To address the above issues, Figure 2 illustrates the flowchart of the research methodology to facilitate coordination of the above three priority objectives in an integrated manner**.**

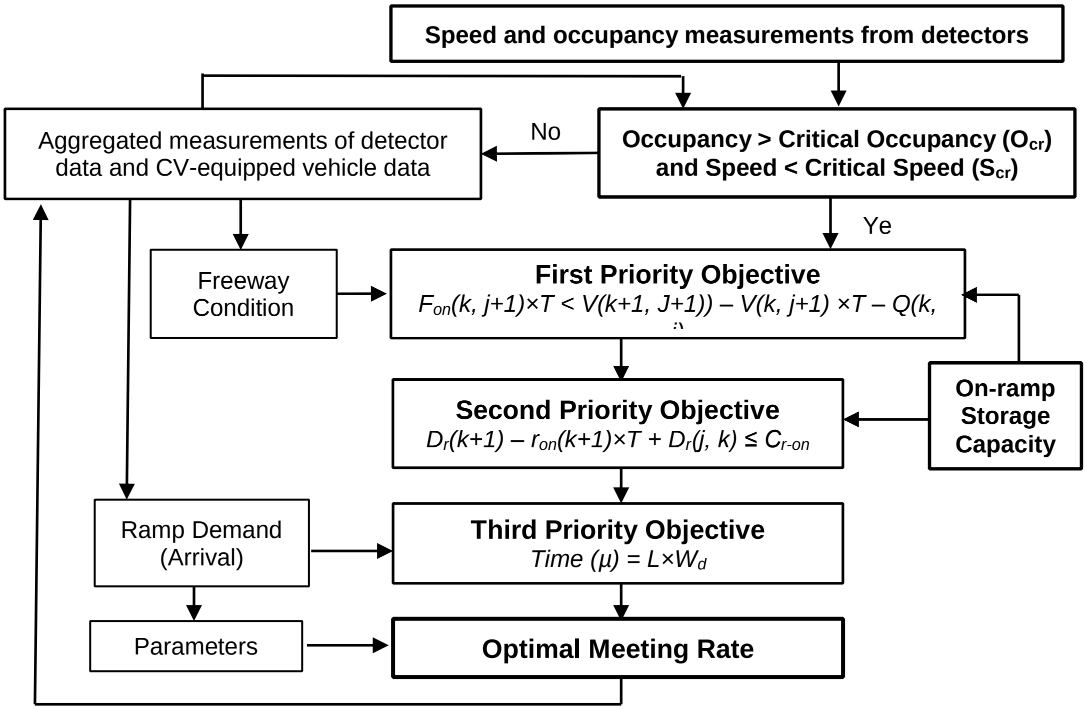


Figure 2: Flowchart of Integrated Ramp Meting Control Algorithms

Both *speed* (*s*) and *density* (*d*) are used for congestion detection. The density, *d(k, j)*, is used as a surrogate in practice and calculated by the following equation.

$$d(k, j) = \frac{O(k,j)}{l(k,j)} \quad (5)$$

where, *O(k, j)* is the occupancy; *l(k, j)* is the length of detectors (the upstream detector at k and the downstream detector at location *k+1*. The congestion is detected if

$$d(k, j) > d_{cr} \text{ and } s(k, j) < s_{cr} \quad (6)$$

where, d_{cr} is the pre-specified critical density value and s_{cr} is the chosen critical speed value. With the availability of V2I data, *d(k, j)* may be measured by CV sensing data.

3.2.1 First Priority Objective

$$F_{on}(k, j + 1) \times T < V(k + 1, j + 1) \times T - V(k, j + 1) \times T - Q(k, j) \quad (7)$$

where, *Q*(*k*, *j*) is the number of queued vehicles at time k; F_{on} (*k*, j +1) is the detected on-ramp inflow rate; and *V*(*k*, *j+1*) is the mainstream flowrate. The upper limit of *Q*(*k*, *j*) can be estimated by quantifying the number of vehicles within a freeway section [10].

Vehicles are allowed to merge into the freeway only when a minimum headway is found on the rightmost lane which merges with on-ramp [11]. This strategy does not only help control the on-ramp flow into freeway, but also delays the formation of internal perturbations at the upstream of the ramp.

3.2.2 Second Priority Objective

To avoid possible queue spillback from the on-ramp, the second priority objective is set up by the following equation.

$$D_r(j+1) - Q_{rm}(j+1) \times T + Q_r(j) \leq C_{r-max} \quad (8)$$

where, $D_r(j+1)$ is the traffic demand on on-ramp at interval j+1 and is estimated from the demand measured at the previous interval [12]; $Qr(j)$ is vehicles stored on the on-ramp at the end of interval j; and Cr is the storage capacity of on-ramp.

3.2.3 Third Objective

The primary purpose of the third objective is to minimize the impact of shockwave propagation on formation of freeway congestion.

4 PRELIMINARY CASE STUDY

4.1 Design of Testing Scenarios

The I-71 at Exit #12 (Northbound) and Kenwood Road (southbound) in Cincinnati, Ohio (Figure 3), a recurrent congestion site mainly caused by large ramp flows is considered for deployment of ramp metering control systems.

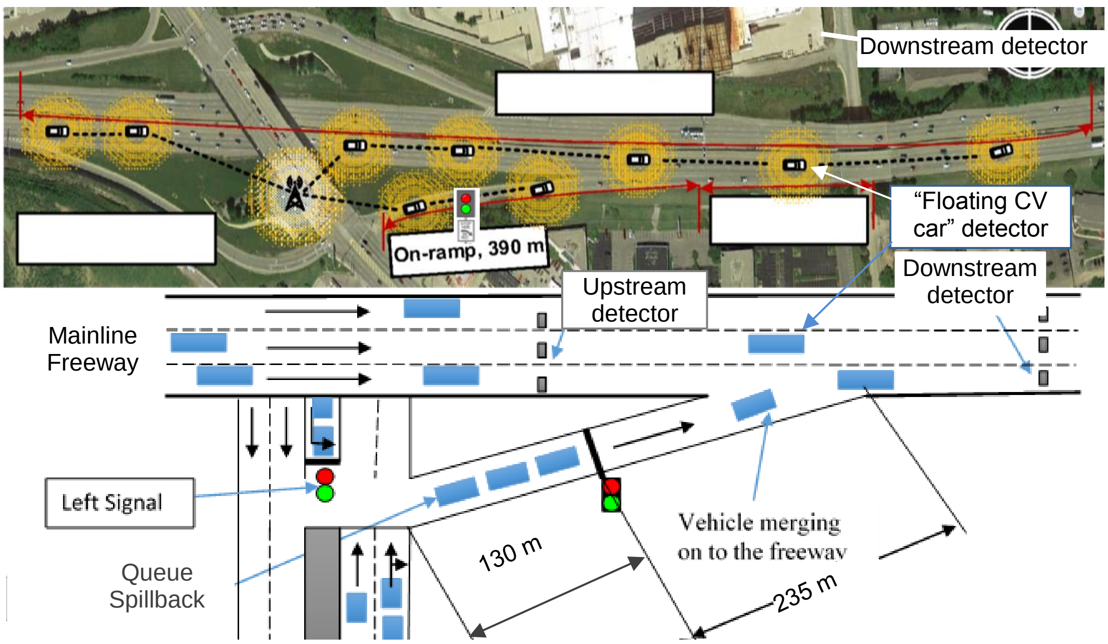


Figure 3: Illustrated Layout of Case Study Site and Loop Detector Locations.

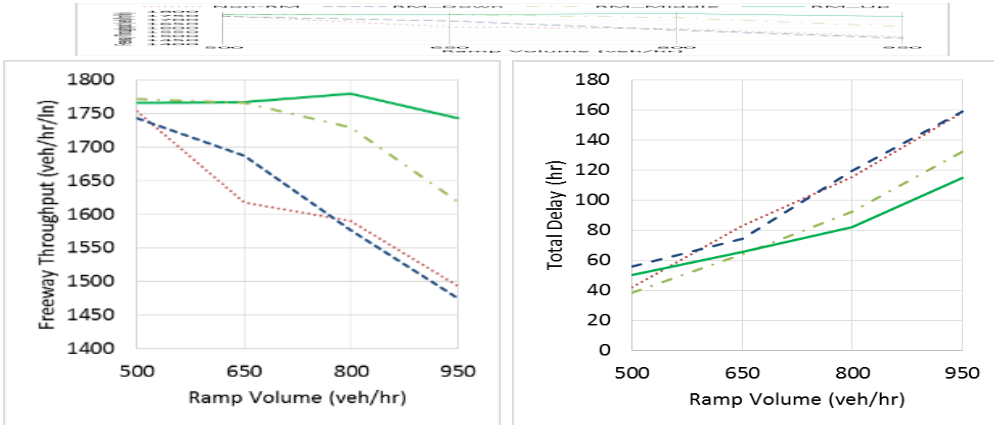
Scenario: 1 – The base scenario where the intersection of Kenwood Road and the on-ramp is signalized. This scenario is to measure the performance of ramp metering for the proposed algorithm and ALINEA algorithm without considering CV's impact. The signal is coordinated between the ramp meter and the arterial signals.

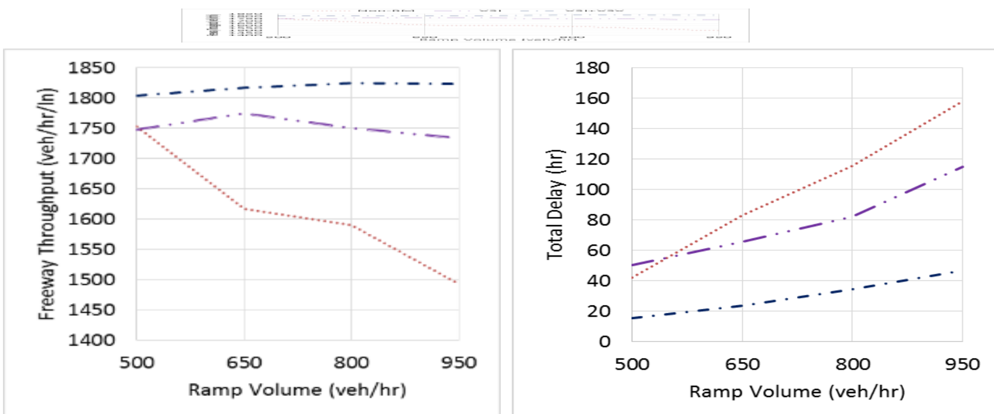
Scenario: 2 – This is the multi-detector scenario where vehicles' count and occupancy data are obtained at three locations of I-71 North, i.e., RM_Up, RM_Middle and RM_Down locations (Figure 4). In general, the ramp meters cannot achieve the control objective because they cannot provide correct traffic information as they are placed outside the region where traffic congestions usually occur. To address this problem, a better detector location should be identified such that the detectors will be able to capture the congested traffic condition. To this end, two new detector locations are tried in this study. One detector location is in the middle of the acceleration lane, 65 meters downstream from the beginning of the acceleration lane at the on-ramp north. The other detector location is 30 meters upstream from the beginning of the acceleration lane. The new detector locations are displayed in Figure 3.

Scenario 3 – This is a scenario of the CV-equipped traffic flows with the V2I+V2V support. CV-equipped vehicles are viewed as “floating sensors” enabling V2I and V2V.

4.2 Results and Discussion

The simulation-based testing result for Scenario 1 suggests improvements achieved by the proposed integrated ramp metering algorithms over the ALINEA. For example, the average on-ramp delay is reduced from 8.3 sec/veh with the ALINEA to 5.2 sec/veh, accounting for 37.3% delay reduction, whereas the on-ramp traffic throughput maintains almost at the same level. The average freeway delay is reduced from 37.4 sec/veh with the ALINEA to 30.1 sec/veh, accounting for 19.5% delay reduction, whereas freeway traffic throughput remains almost the same.





MOE Comparison of No-Ramp with Scenario 2

MOE Comparison of No-Ramp Case with Scenarios 2 and 3

Scenario 2 **Scenari**

Figure 4: Performance Comparison of Different Loop Location Cases.

Figure 4 shows MOE comparison of Scenarios 2 and 3 with the case of no ramp (or non-RM case). Scenario 2 showcases when detectors are assumed at different locations. The traffic operation at medium to high ramp volumes (i.e., 650 veh/hr to 950 veh/hr) is improved by better measuring the congested traffic using the detected data from RM_Middle and RM_Up detectors. The higher the ramp rate is, the greater the influence of the ramp meters is. Overall, the RM_Up case has the best performance among the three RM cases. But multiple detectors still brings limited improvement. Scenario 3 shows a solution by using the CV technology, outperformancing Scenario 2 in terms of increased throughputs and reduced delay on both freeway and ramps.

5. CONCLUSIONS

The research's contribution includes: 1) integrated modeling for optimizing ramps and local arterials by using the CV equivalent "floating sensors"; 2) synthesis on systematic evaluation of traffic operation and mobility in the envisioned CV environment; and 3) measures to investigate and measure efficiency of traditional detectors and CV-enabled detection. The case study of a realistic ramp metering system positively support the benefits of the synthetic modeling approach.

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