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Controlling Detour Vehicle Volume for Stable Congestion Mitigation in Route Guidance Systems

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Vehicle route control is a promising approach for addressing traffic congestion caused by temporary changes in road capacity, such as traffic accidents and road construction. Several studies have proposed to guide vehicles to bypass congestion and thus alleviate it. However, this method stops route control immediately after the congestion disappears, resulting in the reoccurrence of congestion and road instability. To overcome this problem, we propose a method called congestion management based on in- and outflow volumes (COMIO), which stabilizes traffic by controlling the detour traffic volume until congestion is truly resolved. Our method works in tandem with a conventional route guidance method, where the conventional method detects congestion and computes detour paths and COMIO gradually controls the detour traffic volume over time until the congestion disappears. The key strategy of our method is to manage the balance of the inflow and outflow of the congested road. By maintaining the inflow volume a certain amount smaller than the outflow volume, congestion is gradually reduced without rapid traffic changes and finally disappears without its reoccurrence. COMIO offers stable traffic control during traffic congestion resolution, resulting in more efficient traffic control for the entire road network.

1. Introduction

Sensors and IoT are widely used as digital tools to improve society, and vehicle transportation systems are one of their major applications. Recently, intelligent transportation systems have attracted attention, and technologies that measure the traffic state on road maps via roadside units (RSUs)(1) or cellular connections are gradually becoming more widespread.(2,3) Such traffic measurements and vehicle connectivity have the potential to control vehicle traffic to optimize efficiency. At the same time, the number of automobiles is increasing worldwide, and traffic jams have become a major social problem due to the associated economic losses and environmental pollution. Traffic congestion occurs when traffic demand exceeds road capacity and is especially apt to occur when events such as traffic accidents and road construction occur. However, effective countermeasures have not yet been developed.

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Many methods using computer technologies have been proposed to mitigate traffic congestion. The two primary approaches are traffic signal control[4–8] and vehicle route control.[9–17] The former controls traffic signal patterns and durations according to the traffic demand at each intersection, or synchronizes the patterns among multiple intersections to improve the efficiency of traffic. However, this approach has limited performance in dealing with traffic congestion caused by temporary large changes in road capacity due to traffic accidents and road construction, and vehicle route control is the more promising approach for addressing such traffic congestion.

Several route guidance methods have already been proposed. Hart *et al.* proposed a route guidance method called dynamic shortest path (DSP), which detects congestion, identifies nearby vehicles about to enter a congested road, and notifies them of their shortest-path-based detour routes, thus mitigating the congestion.[9] Pan *et al.* proposed the use of the *k* shortest paths method in route guidance when congestion is detected, as well as several methods to distribute traffic into multiple paths, such as the random *k* shortest paths (RkSP) and entropy-balanced *k* shortest paths (EBkSP) methods.[10] Matsui and Yoshihiro proposed a method of providing detours for vehicles located even far from a congested road to achieve more efficient congestion mitigation.[17] However, those route guidance methods are stopped immediately after the congestion has been mitigated. Since the root cause of the congestion may not yet have been removed, congestion will reoccur, and the traffic on the route network will be unstable.

Currently, methods of stabilizing traffic in route guidance are lacking. Since rapid changes in the detour volume lead to traffic instability, sufficient control of the detour volume is essential to stably mitigate congestion via route guidance. Congestion will disappear when the root cause, such as a traffic accident, is removed and the road capacity exceeds the traffic volume. Maintaining an appropriate volume of detouring traffic based on the measured traffic conditions until the root cause is removed is thus necessary.

In this paper, we propose a method called congestion management based on in- and outflow volumes (COMIO), which controls the detour traffic during congestion. COMIO works in tandem with a conventional route guidance method, with the conventional method detecting congestion and computing detour paths and COMIO controlling the detour volume. The key strategy of our method is to manage the balance between the inflow and outflow volumes of the congested road. By maintaining the inflow volume a certain amount smaller than the outflow volume, congestion will gradually decrease without rapid changes in the traffic conditions. By managing the balance of inflow and outflow even after the congestion disappears until the required detour volume has slowly reached zero, we stably manage congestion in cooperation with route guidance methods.

This paper consists of six sections. Section 2 describes the related work. Section 3 describes the proposed method. Section 4 provides the evaluation methods and reports the results obtained with a vehicle traffic simulator. After we provide a discussion in Sect. 5, we finally summarize the study in Sect. 6.

2. Related Work

The two main approaches for mitigating traffic congestion are traffic signal control(4–8) and vehicle route control.(9–17) These methods increase the traffic capacity of the entire road network by encouraging vehicles to travel more efficiently. The former approach improves the efficiency of the whole traffic system by dynamically controlling the phase time of traffic signals. For example, the Sydney Coordinated Adaptive Traffic System (SCATS)(5) and the Split-Cycle Offset Optimization Technique (SCOOT)(6) are well-known signal control methods that have been implemented in the field. Many other advanced signal control methods have also been proposed.(4,7,8) However, signal control alone is not suitable for solving congestion caused by temporary causes such as traffic accidents because it cannot reduce congestion speedily.

Vehicle route control is a promising approach for coping with congestion because it can rapidly reduce the volume of traffic entering a congested road. DSP is a simple route guidance method that suggests the shortest route while avoiding congested roads for vehicles about to enter them.(9) Rezaei *et al.* proposed another shortest-path-based method that minimizes the travel time to the destination.(11) De Souza *et al.* proposed a method that computes the shortest paths weighted by traffic density.(12) These simple methods are effective but their performance is limited because they use only one detour path, resulting in the concentration of vehicles in the case of congestion.

In a multiple-detour-paths method, a k shortest paths algorithm is often adopted.(18) Pan *et al.* proposed the RkSP method, which distributes vehicles randomly among k shortest paths.(10) In the same paper, they also proposed the EBkSP and flow-balanced k shortest paths (FBkSP) methods. De Souza *et al.* proposed the distribution of traffic among k shortest paths according to the Boltzmann distribution.(13) However, these methods do not coordinate traffic among the different detour routes, resulting in the concentration of traffic on certain roads on the detour routes. Thus, Liu *et al.* proposed a method of avoiding the concentration of vehicles on detour routes by coordinating detour routes among vehicles via a bidding mechanism.(14) Guidoni *et al.* (15) and Liu *et al.* (16) proposed load-balancing methods that reflect the traveling paths of each vehicle in the weights used in the shortest-paths computation in real time. Matsui and Yoshihiro proposed a capacity-aware detour route guidance method that calculates detours for vehicles not only near congested roads but also far from them, and schedules vehicle detours so that the capacity of roads in the detour paths is not exceeded.(17) However, these methods still lack traffic volume control to maintain stability on the whole road network.

As outlined above, real-time traffic volume control is lacking in route guidance methods. To the best of our knowledge, this is the first study to introduce traffic volume control into route guidance methods to mitigate traffic congestion.

3. Proposed Method

3.1 Overview of the proposed method

The proposed method, COMIO, computes the volume of vehicles detouring around a congested road segment to balance the inflow and outflow volumes on that segment. When congestion is detected, to decrease the vehicle volume on the congested road, COMIO computes the volume of detouring vehicles so that the inflow volume of the congested road remains a certain amount lower than the outflow volume. This operation stabilizes traffic volume fluctuations on congested roads, thereby relieving congestion stably. Even after the congestion has disappeared, the proposed method does not stop detouring vehicles immediately. This is because, if the detour guidance is stopped suddenly, the traffic volume on that road will increase rapidly and cause congestion again. Therefore, in this paper, we propose a method of controlling the detour volume not only during congestion but also after the congestion has disappeared, thus stabilizing the traffic on the road network. This method continues to detour vehicles until the root cause of traffic congestion, such as lane closure caused by a traffic accident, has been eliminated and the required detour volume has slowly been reduced to zero.

3.2 Assumptions

COMIO is applied to control the volume of traffic that is guided onto detour routes computed by a conventional detouring scheme. As mentioned above, several route guidance methods such as DSP[9] have been proposed as countermeasures against traffic congestion. They basically start detouring when congestion is detected and stop detouring as soon as congestion is no longer detected, often leading to repeated congestion. We assume that a route guidance method is applied, with COMIO controlling the volume of traffic guided onto detour routes. Specifically, we assume that the conventional method detects congestion when the vehicle density on a road segment exceeds a threshold value. The conventional method also computes detour routes that bypass the congested segments. We start to control the detour traffic volume when congestion is detected, and continue controlling it even after the congestion has disappeared, slowly decreasing the detour volume to zero until detouring is no longer required. This strategy provides more stable and efficient congestion management than the conventional method alone, which does not control the volume of detouring traffic.

We assume that RSUs are installed at various locations in the target road network or that all vehicles are connected so that traffic volumes on all roads can be monitored. We focus on a centralized control system in which a central server computes the detour routes as well as the detour traffic volumes, rather than a distributed control system in which vehicles compute their own detour routes. Therefore, we assume that the required traffic state on the whole road network is collected at the central server via the RSUs or cellular connections. When congestion is detected, the central server computes detour plans, consisting of the detour routes and traffic volumes of the whole road network, and guides vehicles to the detour routes via RSUs or cellular connections.

Each vehicle is allowed only one detour; if the vehicle encounters traffic congestion on a detour route, it is not guided to another detour. We adopt this policy for two reasons. First, from the user's point of view, the travel time for vehicles following multiple detour guidances may increase significantly, which could significantly increase the travel time and invoke a sense of unfairness. Second, from the global viewpoint, rerouting again at the detour route causes the congestion of other roads, and congestion could spread from road to road, leading to the instability of traffic on the entire road network. This chain of congestion sometimes results in a significantly inefficient traffic situation. To avoid such inefficiency, we adopt a policy of not guiding vehicles that have already been rerouted once.

3.3 Notation

We define the inflow volume I_r^t and outflow volume O_r^t as the numbers of vehicles entering and exiting road segment r at time t per unit time, respectively. The detour volume D_r^t is defined as the number of vehicles at time t that are guided to change from the original route passing through congested road segment r to another route that avoids this segment per unit time. We define U as the set of road segments that are possible starting points of the detour route and $d_{(u,r)}^t$ for $u \in U$ as the volume of traffic that is guided at time t to a detour route starting from road segment u and avoiding congested segment r. Then, we can write $D_r^t = \sum_{u \in U} d_{(u,r)}^t$. We also assume that the central server can estimate the travel time for the vehicle to pass each road segment. Let $travel_{(u,r)}^t$ express the estimated travel time from the detour starting point u to congested segment r along the original route. Then, the effect of the detour guidance at time t with volume D_r^t will appear on r at time $t + travel_{(u,r)}^t$.

After traffic congestion disappears as a result of detour guidance, even if the congestion is no longer detected, COMIO continues detouring a certain volume of traffic to keep the road traffic stable and prevent the reoccurrence of congestion. If the root cause of the congestion is not removed, the detour volume will not reduce to zero with a balance between inflow and outflow. The detour volume decreases and reaches zero only when the root cause is removed. In this study, we consider that traffic congestion is resolved when its cause (if one exists), such as a traffic accident or traffic restrictions, is removed and the required detouring volume reaches zero, rather than when congestion disappears as a result of route guidance.

3.4 State transition

The central server assigns each road segment a state based on its condition. There are two road states: *normal* and *congested* states. Figure 1 illustrates the transition of the road state. A road segment is in the normal state if no congestion is detected on it. Since a road r in the normal state does not need to reduce the inflow volume, the detour volume D_r^t at any time t is zero. Road segments in the normal state can be included in the detour routes to bypass other congested roads. If congestion is detected in a road segment, it transits to the congested state. Conventional detouring methods compute a set of routes that detour the congested road segment r and sometimes determine the ratio of traffic volume injected to the detour routes. Therefore, COMIO computes the total traffic volume to guide detouring based on the balance between the inflow and outflow volumes. Even if the congestion disappears on a road in the congested state and congestion is no longer detected on it, the road segment continues to be in the congested state. Different from the conventional methods, the proposed method attempts to reduce the detour volume, finally making it zero after the root cause of the congestion (if one exists) has been eliminated. If the detour volume for segment r successfully reaches zero at time t, it transits to

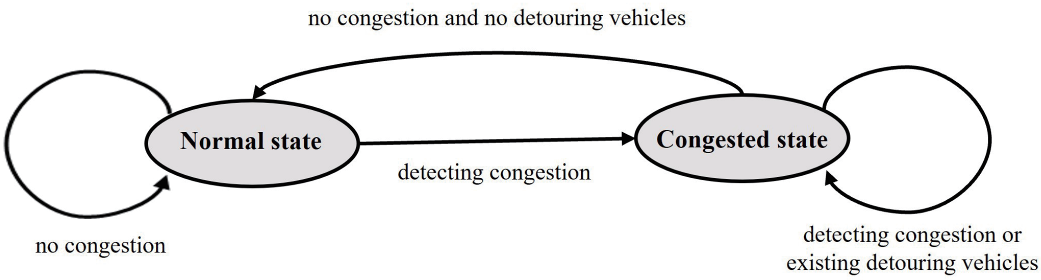


Fig. 1. Transition of road state.

the normal state at time $t + travel^t_{(u,r)}$, i.e., after the entire effect of the detours has been reflected in *r*.

Although the conventional methods essentially have the same state transitions as the proposed method, they immediately terminate the detour guidance when congestion disappears, resulting in re-congestion. By extending the duration of the congested state, COMIO continuously controls the traffic and achieves the efficient and stable management of traffic congestion until its effect is truly eliminated.

3.5 Computing the detour volume D^t_r

The detour volume D^t_r in the congested state is computed as follows:

$$D^t_r = I^t_r - O^t_r + R^t_r + E^t_r. \tag{1}$$

Here, the *reduction* R^t_r is defined as the ideal value of the difference between the inflow and outflow volumes on road segment *r* at time *t*, and the *detour effect* E^t_r is defined as the estimated reduction in traffic volume from the inflow at time *t* due to past detour guidance decisions. The inflow volume I^t_r and outflow volume O^t_r are measured by RSUs or vehicle connections. R^t_r and E^t_r are computed from traffic measurements aggregated in the central server. The calculation methods for R^t_r and E^t_r are described in Sects. 3.6 and 3.7, respectively.

$I^t_r - O^t_r + R^t_r$ in Eq. (1) is employed to control the relationship between the inflow and outflow volumes on road segment *r*. Detouring vehicles to bypass the congested road segment *r* reduces the inflow on *r* by the detour volume. To relieve congestion, the inflow volume of *r* must be lower than the outflow volume. If we assume that the reduction R^t_r and detour effect E^t_r are both zero, then the detour volume D^t_r equals $I^t_r - O^t_r$, with which we intend to control D^t_r such that the inflow volume of *r* will equal the outflow volume. Therefore, by setting R^t_r positive and the detour volume D^t_r as $I^t_r - O^t_r + R^t_r$, the outflow can be kept greater than the inflow by R^t_r. The larger the reduction R^t_r is, the larger the difference will be between the inflow and outflow volumes of road segment *r*.

However, computing the detour volume D^t_r simply as $I^t_r - O^t_r + R^t_r$ does not stabilize traffic on congested roads, because there is a large delay before the detour effect is reflected on congested road r. As mentioned earlier, the delay from the detour start road u to the congested road r is equal to the travel time $travel^t_{(u,r)}$. In other words, the vehicle detour guidance method can be regarded as a feedback system with a large delay, and the detour volume D^t_r must be complemented to reduce traffic volume fluctuation. To suppress the fluctuation of traffic volume due to the feedback system, COMIO adds the detour effect E^t_r to $I^t_r - O^t_r + R^t_r$ to compute the detour volume D^t_r. E^t_r represents the reduction in the estimated traffic volume on r at time t as a result of past detour decisions. That is, if $D^t_r = E^t_r$, we continue providing the same effect volume as currently appearing on road r, leading to stable traffic control on r.

As another issue on vehicle detouring, we introduce the proportion of drivers that follow the guidance of the system. In the vehicle detour guidance method, the system provides detour routes to the drivers. The actual number of detouring vehicles may be less than the number of vehicles that were guided to detour routes. Therefore, it is necessary to make some adjustments by defining the proportion of vehicles that follow the guidance as β $(0 < \beta < 1)$, i.e., βD^t_r vehicles are expected to detour.

When congestion is detected on multiple roads, all these roads transit to the congested state. A route guidance method computes a set of detour routes for each congested road, and our method controls the detour traffic volumes for all the congested roads. That is, the above traffic control process works in parallel for each congested road. Note that, in this study, we do not use congested roads when computing detour routes.

3.6 Reduction R^t_r

We compute the reduction R^t_r for the congested state as

$$R^t_r = \begin{cases} -\alpha N_r, & s^t_r < \dfrac{\gamma}{2} \\ \dfrac{2\alpha\left(s^t_r - \gamma\right)N_r}{\gamma}, & \dfrac{\gamma}{2} \le s^t_r < \dfrac{3\gamma}{2} \\ \alpha N_r, & \dfrac{3\gamma}{2} \le s^t_r \end{cases} \tag{2}$$

where s^t_r is the stay time, defined as the average time spent on r by vehicles located on road r at time t, both α and γ are constant values, and N_r is the number of lanes on road r. Equation (2) is illustrated in Fig. 2. Note that s^t_r indicates the vehicle density level of road r because it is affected by the vehicle speed and the waiting time due to traffic signals. Therefore, in Eq. (2), when the vehicle density level is larger, R^t_r is made larger to increase the difference between the inflow and the outflow, resulting in the congestion being relieved faster. On the other hand, when the vehicle density level is sufficiently small, R^t_r takes a negative value to increase the inflow volume and reduce the detour volume to help gradually return to the usual situation. In this way, COMIO controls the inflow volume such that the vehicle density level on r is always moderate. Note that γ represents the density level for which the inflow and outflow should be equal, and α is used to

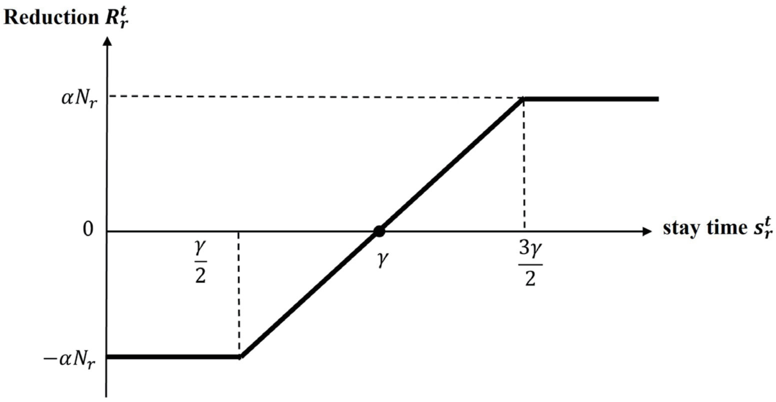


Fig. 2. Computation of reduction R_r^t.

create a floor and a ceiling in the reduction R_r^t. Also, by multiplying by the number of lanes N_r, we exclude the effect of lanes.

In COMIO, we periodically measure the stay time s_r^t and update the reduction R_r^t. Remember that we assume all vehicle behaviors to be collected by the system via RSUs or network connections. Thus, we can obtain s_r^t for vehicles on road r at regular intervals.

3.7 Detour effect E_r^t

The detour effect E_r^t denotes the reduction of the traffic volume from the inflow at time t caused by past detour decisions. During the congestion state of r, multiple detours are made to avoid r, and the inflow volume is reduced by that volume. E_r^t is the reduction in the traffic volume computed in consideration of the delay between the detour decision and the time it affects the inflow volume of r. Suppose that r is congested and that part of the traffic is detoured from road u upstream of r. We estimate the time at which the detour effect is reflected on r as the previously defined value $travel_{(u,r)}^t$, the expected time taken from u to r. Note that when we make detours for road r, we usually have several such upstream intersections u from which detour traffic is generated. Using their estimated time delays, we calculate the detour effect E_r^t as the sum of the traffic volumes that will be reflected on r at time t.

We use a priority queue to calculate E_r^t. Each entry in the priority queue consists of the effecting time $t + travel_{(u,r)}^t$, which is the time at which the detour guidance takes effect, and the traffic detour volume. The effecting time is estimated from the latest stay time s_r^t measured on each road to reach r. We add an entry to the priority queue at regular intervals when the detour volume is updated. Since each detour route may have a different starting road segment u, and the time that the effect is reflected on congested road segment r differs, multiple entries corresponding to each detour route may be added to the priority queue each time the detour volume for r is updated. The computations of the detour routes and the traffic distribution among those detour routes are outside the scope of the proposed method, and we leave them to the conventional route guidance method employed simultaneously with the proposed method.

COMIO computes the detour volume for each congested road at regular intervals. When the time t for calculating the detour volume is reached, all the entries in the priority queue whose effecting time is earlier than time t are retrieved, and the detour effect E_r^t is calculated by summing all the retrieved entries for r.

Then, the detour volume D_r^t is calculated from Eq. (1). To avoid fluctuation of the detour effect E_r^t, we take the moving average of this value over the window from one cycle t_{sig} before to one cycle after the traffic signal, i.e., the window used to obtain E_r^t at time t is from $t - t_{sig}$ to $t \quad t_{sig}$. Note that $E_r^{t'}$ for a future time t' required for taking a moving average can be calculated from the entries in the priority queue. After determining the value of D_r^t, a new entry is inserted into the priority queue that is based on the new detour volumes on each detour route. Repeating this process adjusts the detour volume at regular intervals.

4. Evaluation

4.1 Method

We perform simulations to confirm that the proposed method, COMIO, improves the efficiency of traffic control on the road network. In our scenario, lane restrictions cause traffic congestion, and the proposed method resolves the congestion. We implement COMIO in tandem with a conventional detour guidance method, and compare its performance with the conventional method without COMIO. As the conventional method, we adopt DSP,[9] one of the most basic route guidance methods, which is suitable for measuring a baseline performance for comparison with COMIO. Simulation for Urban Mobility (SUMO)[19] is used as the traffic simulator, and a traffic control interface (TraCI)[20] is used to control the traffic in SUMO for the conventional and proposed methods. By evaluating the travel time for vehicles to arrive at their destinations, we confirm that the proposed method controls the traffic on congested roads and also the entire road network more efficiently than the conventional route guidance method alone.

We compare the performance of DSP with and without COMIO. Specifically, DSP in this paper works as follows. (1) At regular intervals, DSP attempts to detect congestion on all roads. (2) If congestion is detected on any of the roads, DSP identifies vehicles located within distance L from a congested road to guide detouring and gives priority as described in Ref. 9. (3) COMIO computes the number of vehicles to guide and chooses the number of vehicles with respect to the given priority. (4) DSP guides the vehicles chosen to detour. Note that DSP without COMIO skips step (3) and instead guides all vehicles identified in step (2) to detour.

In this study, we assume a road network with traffic lights and that the central server controls the traffic on the basis of measurements of traffic volume, and so forth, on the road network. Note that traffic volume measurements vary depending on the timing of the traffic signal. Namely, if the signal is green, the traffic volume increases, and if the signal is red, the traffic volume decreases. To prevent this fluctuation of the measurements due to traffic lights, we use the average traffic volume over one signal cycle of traffic lights.

4.2 Scenario

In this simulation, we use the Osaka City road network shown in Fig. 3, which is obtained from OpenStreetMap.[21] We remove narrow roads to create a road network with only major roads so that vehicles use the shortest paths and the detour paths consist of major roads. Traffic lights are installed at all applicable intersections because all the included intersections in the road network are major intersections.

Vehicles are generated at edge roads of the network and arrive at the other end of the edge roads. Specifically, we generate vehicles from every edge road of the road network. For instance, vehicles generated at a left-side edge are going to an edge road of either the top-, right-, or down-side of the map. We generate traffic flows for all such pairs of edge roads of the map so that the ratio of traffic volume on each edge road corresponds to the result of an official Japanese survey.[22] SUMO automatically computes the shortest paths for vehicles based on their source and destination roads.

In this simulation, to generate congestion on the road network, we close lanes on a road with high traffic volume that acts as a bottleneck. The road with the lane closure is at X in Fig. 3, where we close the two right-hand lanes of the three lanes at X.

The simulation settings are given in Table 1. The simulation starts at 0 s and ends at 36000 s. Vehicles are generated between 0 and 30000 s. The two lanes are closed from 3600 to 10800 s. Then, we evaluate the traffic efficiency with the vehicles departing from their source road between 1800 and 14400 s, intending to exclude the time duration of sparse traffic. We generate traffic volumes for the entire road network of 9000 to 13000 vehicles/h, where the negative effects of lane closures are hardly observed in the case of 9000 vehicles/h, but serious congestion occurs at 13000 vehicles/h.

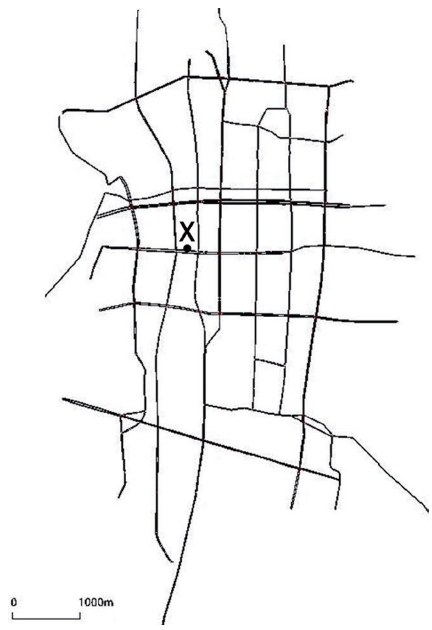


Fig. 3. Road network of Osaka City.

Table 1
Simulation settings.

Traffic simulator	SUMO[23]
Simulation time	0–36000 s
Vehicle appearance time	0–30000 s
Lane closure time	3600–10800 s
Vehicle used for evaluation	Vehicle departing time 1800 to 14,400 s
Traffic volume	9000, 10000, 11000, 12000, 13000 /h
Signal period	120 s
Congestion detection cycle	20 s
Traffic acquisition cycle	20 s
Congestion detection threshold	0.5
Estimated probability of following route guidance	0.8
Actual probability of following route guidance	0.7
Level L	1, 2, 3
α	0.6, 0.8, 1.0, 1.2, 1.4
γ	120 s

In this simulation, the traffic congestion detection procedure is invoked every 20 s. When congestion is detected, the central server computes the detour guidance plan that will be executed from the current time to the next congestion detection time. Congestion on each road is detected by applying a threshold on the vehicle density of $0.5 \times V_{max}$ in accordance with a traffic flow model called Greenshield's model,[23] where V_{max} is the maximum density of the road segment. V_{max} is calculated for each road as $N_{max}/length$, where N_{max} is the maximum number of vehicles in the road and *length* is the road length, and N_{max} is calculated as the road length divided by the vehicle length. In this simulation, the vehicle length is set to 7.5, which is the sum of SUMO's default setting of the vehicle length of 5.0 and the minimum distance from the vehicle in front of 2.5.

As the parameters in the simulation, γ is set to 120 s and α is set to 0.6, 0.8, 1.0, 1.2, and 1.4. The signal cycle is set to 120 s. The interval for updating the detour road volume is set to 20 s, the same as the congestion detection interval. The probability of vehicles following the route guidance is set to 0.7, meaning that vehicles do not change their own routes with a probability of 30% even if we provide route guidance.

4.3 Results

4.3.1 Preliminary experiment: level *L*

Several conventional route guidance methods including DSP have a parameter L. When congestion is detected on segment r, the conventional methods guide vehicles located within distance L from r whose planned routes pass r, where the distance between roads is measured by the hop count, i.e., the number of road segments passed by the shortest paths. As a preliminary experiment, we compare the performance while varying L to find the best value of L in our scenario.

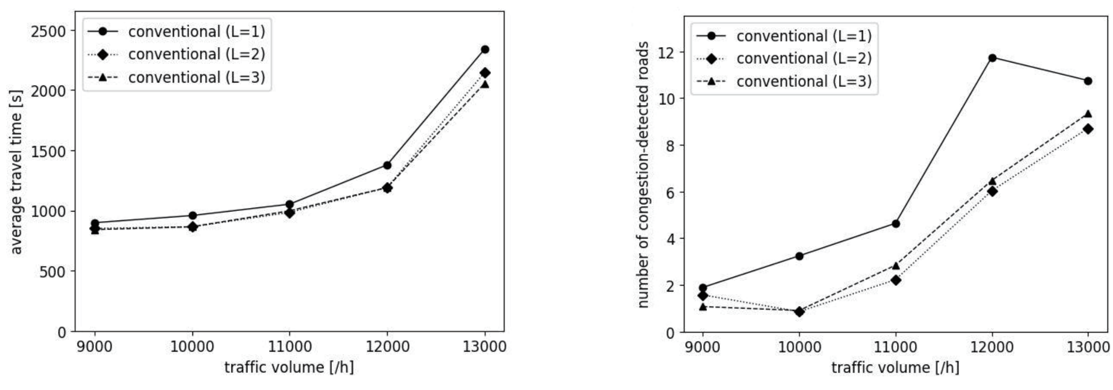
Figure 4 shows the simulation results of DSP without COMIO, illustrating the average of five repetitions with different random seeds for level L of 1, 2, and 3. Figure 4(a) represents the average travel time of the evaluated vehicles, i.e., vehicles departing from 1800 to 14400 s. The travel time is defined as the time duration from departing the source road to reaching the destination road of the vehicles. The results show that L = 2 and 3 gave better performance than L = 1, meaning that the number of detoured vehicles for L = 1 was less than the required number to efficiently resolve the congestion. Figure 4(b) represents the number of congestion-detected roads. Because the performances for L = 2 and L = 3 are similar, we use both values in the main experiment for comparison with the proposed method.

4.3.2 Preliminary experiment: parameter *α*

To find an appropriate value for the parameter α of COMIO in the main experiment, we perform simulations for each value of α. The smaller the value of α, the smaller the range of values taken by the reduction R_r^t and the slower congestion relief will be. In contrast, as α increases, the traffic volume on the road network changes rapidly, making the traffic unstable. Therefore, it is necessary to set an appropriate value of α to improve the efficiency of traffic control. Figures 5(a) and 5(b) give the simulation results, which show the average travel time and the number of congestion-detected roads, respectively. It is found that α = 1.2 gives the shortest average travel time and the fewest congestion-detected roads, and we use this value in the main experiment.

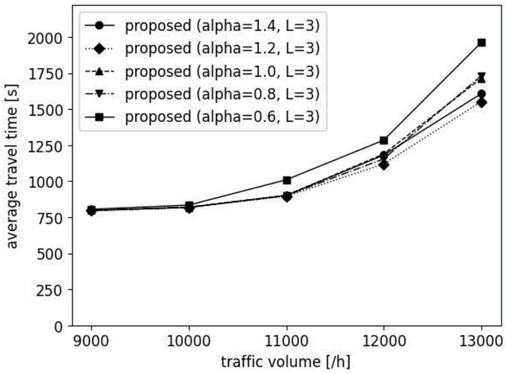
4.4 Main experiment

Using the parameters determined in the preliminary simulations, we perform the main experiment. Figure 6(a) shows the average travel time with five repetitions for different random seeds. For all the traffic volumes tested, the proposed method had the lowest average travel time. Figures 6(b)–6(d) show the average increase in travel time for the vehicles that followed the

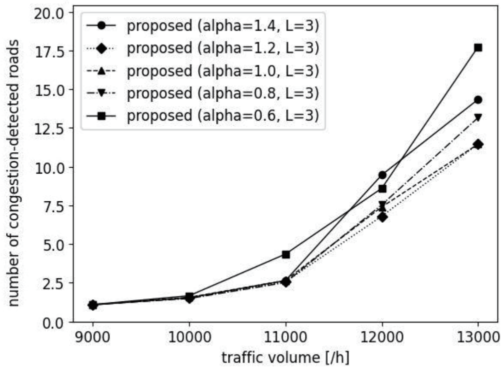


(a) (b)

Fig. 4. Preliminary experiment of conventional method. (a) Average travel time. (b) Number of congested roads.



(a)



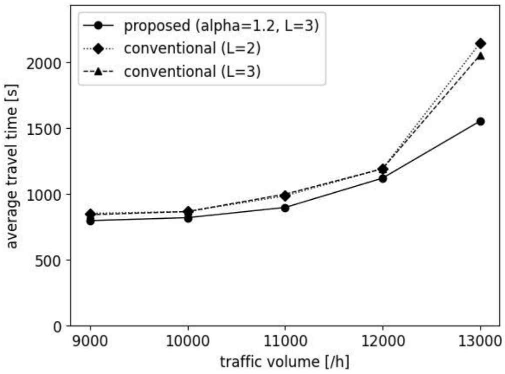
(b)

Fig. 5. Preliminary experiment of proposed method. (a) Average travel time. (b) Number of congested roads.

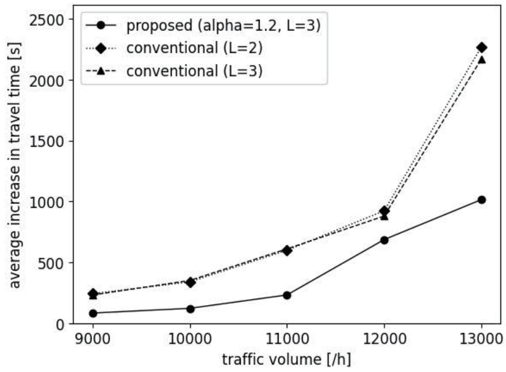
detour guidance, that did not follow the detour guidance, and that were not guided, respectively. Here, the increase in travel time is defined as the difference from the travel time of the same vehicle in the normal case with neither a lane restriction nor route guidance. All these results indicate that COMIO reduced the travel time of vehicles. Specifically, Fig. 6(b) shows that the travel times of the vehicles that made a detour were reduced because they avoided the congestion, Fig. 6(c) shows that the vehicles that enter the congested road had a reduced travel time in the case of severe congestion because the congestion was alleviated by other vehicles taking detours, and Fig. 6(d) shows that even the unguided vehicles had a reduced travel time in the case of severe congestion because of the stabilization of the traffic over the whole road network. Figure 7(a) shows the total number of vehicles that faced congestion after entering the detour routes, meaning that the detouring traffic caused further congestion. Figure 7(a) also shows that the proposed method markedly reduced the occurrence of congestion caused by detour guidance. When the traffic volume was less than 11000, the proposed method resulted in little or no congestion on the detour routes. This is because the proposed method computes the detour volume, whereas the conventional method guides as many vehicles as possible to the detour routes. Figure 7(b) shows the number of vehicles that followed the detour guidance for COMIO and the conventional method. There were fewer guided vehicles for COMIO. These results indicate that the proposed method mitigates traffic congestion with less adverse impact on non-congested roads.

5. Discussion

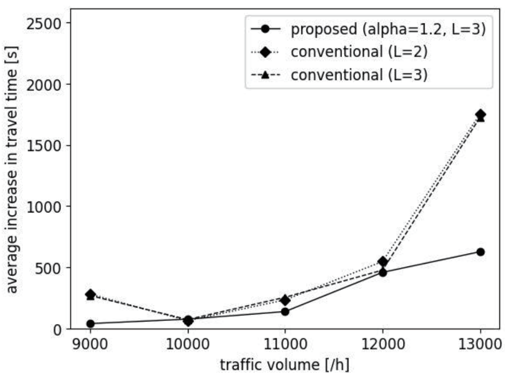
COMIO attempts to avoid rapid fluctuations in traffic volumes and to achieve stable congestion management. Figure 8 shows the traffic conditions (detour volume, flow rate, and average vehicle speed) on a road during the congestion management period. Since congestion on a single road causes a chain of traffic congestion due to detoured traffic and the congestion management process involves multiple detour behaviors for multiple congested roads, a road with the typical flow behavior specific to this method was selected. In the figure, we compared



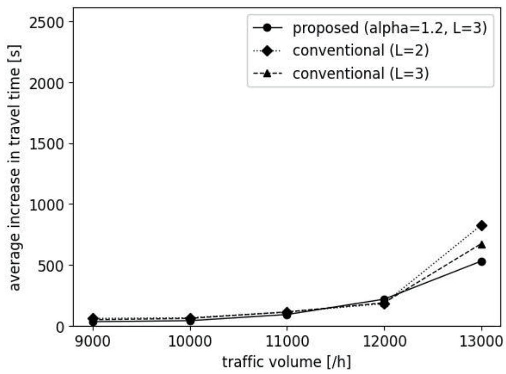
(a)



(b)

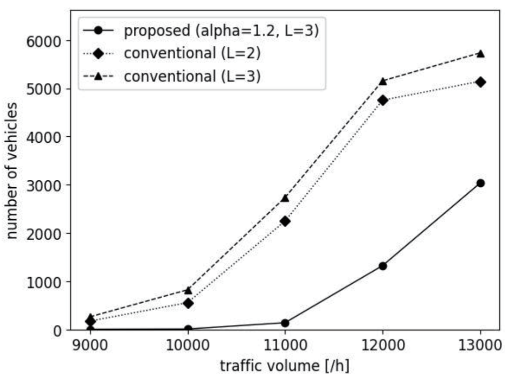


(c)

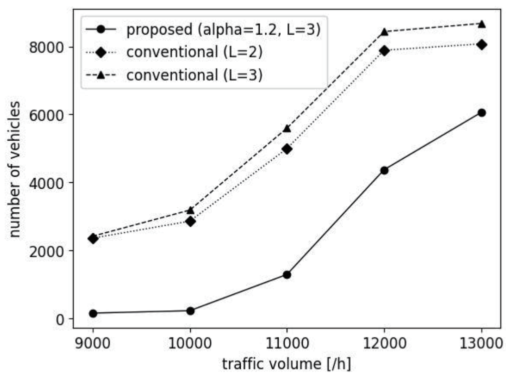


(d)

Fig. 6. Traffic control efficiency. (a) Travel time for all vehicles. (b) Increase in travel time of vehicles following guidance. (c) Increase in travel time of vehicles not following guidance. (d) Increase in travel time of unguided vehicles.

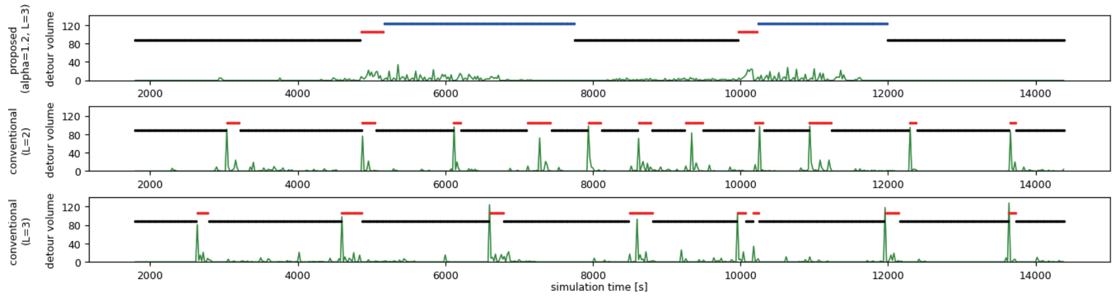


(a)

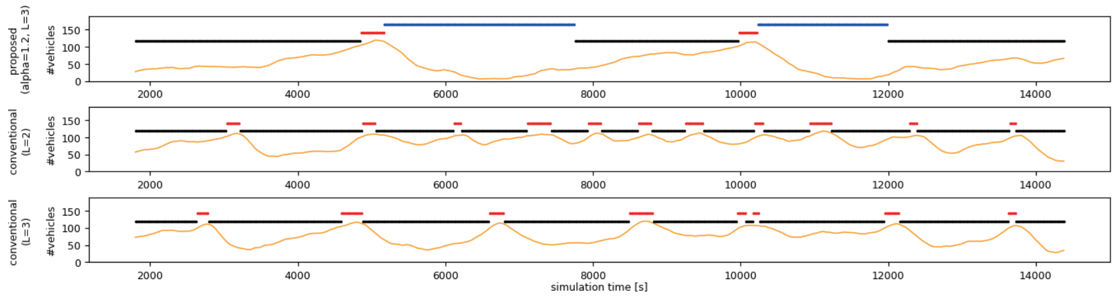


(b)

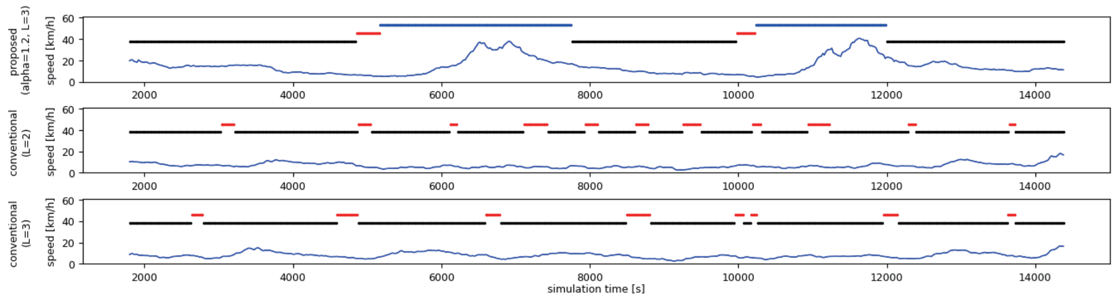
Fig. 7. Impact of detour guidance on traffic congestion. (a) Number of detouring vehicles experiencing congestion on detour routes. (b) Number of vehicles following guidance.



(a)



(b)



(c)

Fig. 8. (Color online) Flow control effect. (a) Detour volume for a congested road. (b) Number of vehicles on a congested road. (c) Average speed of vehicles on a congested road.

the proposed method with the conventional methods with L = 2 and 3, where Fig. 8(a) shows the amount of detoured traffic for the road, Fig. 8(b) shows the number of vehicles on the road, and Fig. 8(c) shows the average vehicle speed on it. In addition, the black markers in the figure indicate that the road is in the normal state, the red markers in the congested state with congestion detected on it, and the blue markers in the congested state without congestion detected, where the blue-marker state is a specific state to COMIO.

Figure 8 also shows that the interval of repeated detour operations varies among the cases. In the conventional method, traffic congestion and detours are repeated at short intervals, and vehicle speeds are always low; in the L = 3 case, the intervals are slightly larger because vehicles are detoured from more distant roads, resulting in slightly greater delays as the detouring effect of the feedback system. The proposed method has the largest interval due to its flow control capability, resulting in smaller detour volume fluctuations and a significant increase in vehicle speed. Although COMIO could not converge traffic volumes after congestion was reduced and detour operations were still repeated, it significantly reduced flow fluctuations both in terms of time and volume, resulting in improved traffic performance. This trend was observed on several roads on the map. It can be concluded that COMIO provides more stable congestion management than without COMIO by balancing inflows and outflows.

6. Conclusions

In this study, we proposed a traffic volume control method, COMIO, that works with a conventional route guidance system to improve the efficiency and stability of congestion mitigation. By maintaining a balance between the inflow and outflow on a congested road, COMIO stabilizes the traffic volume on the congested road as well as on the whole road network throughout the congestion mitigation process. We evaluated COMIO using a traffic flow simulator under the scenario of a lane closure on a road network of Osaka City that would lead to serious congestion. By comparing the performance of the route guidance method DSP with and without COMIO, we found that the proposed method reduces the average travel time for not only the detouring vehicles but also the other vehicles. These results indicate that COMIO enables efficient and stable traffic congestion control.

As future work, eliminating repetitive state transitions in the congestion management process, even when multiple congested roads exist, is one of the essential issues for stabilizing congestion management. Another important future task is to improve the practical applicability of COMIO by considering the penetration ratio of the system and other factors. Although we evaluated COMIO using a real road map of Osaka City, further evaluation using maps of other cities would confirm COMIO's versatility. A further exciting perspective will be to combine route guidance methods with traffic flow prediction methods based on machine learning.

Acknowledgments

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