Evaluation of congestion mitigation effect at sags brought by lane change control using RVC system

Yuuki SHIBUYA Hiroaki MORINO

Graduate School of Engineering and Science
Shibaura Institute of Technology
Tokyo, Japan
{ma18057, morino}@shibaura-it.ac.jp

***Abstract*— Congestion on expressways has become a serious problem and causes serious economic loss. In particular, traffic congestion at sags, triggered by slow down of some cars in uphill sections have been major cause of natural traffic congestion. This paper proposes schemes to control lane change of cars through periodic control message broadcast from the roadside server to cars via road to vehicle communication. In this scheme, the type of lane change control and its parameters are adaptively changed depending on the amount of traffic flow in each lane measured in real-time by vehicle detectors. Lane change controls comprise probabilistic forced lane change which is applied before congestion occurs and lane change restriction which is applied during congestion. The results of traffic flow simulation show that proposed scheme reduces the travel time to pass an uphill section of sags with the configuration of control area considering behaviors of cars before and during congestion.**

Keywords—congestion, mitigation, sag, lane change, road to vehicle communication

I. Introduction

Congestion on expressways has become a serious problem of the world, and causes serious economic loss. Especially in Japan, Ministry of Land, Infrastructure, Transport and Tourism of the Japanese government has announced that Japanese citizens have spent approximately 40% of road travel time per capita on congestion and those could convert labor costs of 2.8 million people, thereby, economic loss might reach 12 trillion yen.

In some of expressways, it has been observed that capacity of the sag segments are lower than flat segments [1]. According to [2], 73% of congestion on expressways in Japan can be attributed to traffic concentration, of which 61% can be attributed to uphill and sag segment. Sags are road segments where gradient changes from downhill to uphill at short notice. It has been observed that some drivers are unaware of changing grade resistance force and vehicle deceleration because of its gentle gradient. It is known that when the congested platoon reaches sag segment and vehicles which are part of this platoon decelerate, the following driver would put on the brakes and occurred deceleration wave would drastically propagate to posterior, consequently, congestion forms at sags. It is also known that utilization of the passing lane would become higher because some drivers who have higher desired velocity. It has been observed that there is a difference between the utilization of two lanes. Furthermore, when utilization of the passing lane is high, congested platoon is formed on passing lane, and the deceleration wave would propagate more sharply than usual.

To cope with this problem, balancing lane change utilization would be effective. In [3] and [4], lane change restriction and balancing lane utilization are presented as part of the congestion study, and show that these control achieved improve travel time of congested section. They performs an experiment in a three-lane expressways in which a Variable-message sign(VMS) is installed at roadside before the congestion-prone section to prompt cars running the middle lane and outer lane to change to the median lane. However, the effectiveness of mitigating traffic congestion by this approach depends on how human drivers are aware of congestion occurrence mechanism and also willing to run at faster speed.

This paper focus on employing RVC(Roadside-to-Vehicle Communication system) to overcome this problem, assuming that autonomous driving cars will be increasingly popular in the near future and most of them are equipped with RVC capability.

In the novel lane change control schemes, base stations of RVC periodically send messages to cars to prompt lane change after detecting initial stage of traffic congestion, based on the traffic flow collected by vehicle detectors provided at roadside. The ratio of cars which conduct lane change is dynamically varied depending on the collected traffic flow. This paper evaluates the proposed scheme by focusing the average velocity at sag, and investigates the appropriate control section where the proposed scheme is applied when congestion occurs.

II. Literature Review

There have been various studies to mitigates congestion on expressways. [5] empirically analyzes lane change patterns which occur before an uphill expressway segment from vehicle detector data. It reveals that lane changes from other lanes to the most heavily utilized lane (e.g. median lane in 3 lanes expressways) disrupts traffic flow and induce congestion, and argues that discouraging these lane changes would be advantageous. Traffic management including lane change control by using ITS or ADAS are extensively studied for mitigating congestion[6][7]. [6] proposes in-car advisory system providing information that including optimal speed, headway, and lane. [7] presents lane change control assuming a road model including a lane drop due to an incident. It shows the control can save travel time by 40-50% in case of 100% penetration rate.

These existing studies do not address evaluation of lane change control for traffic congestion mitigation.

III. Lane Change Control Scheme

This section presents dynamic lane change control by exploiting traffic flow information obtained by vehicle detector at roadside.

Overview of system configuration is illustrated in Fig. 1. This scheme is applied before a section where natural congestion often occurs, such as sags. A vehicle detector is installed in the uphill section to measure traffic flow in each lane. The roadside server creates a lane change control message depending on the measured traffic flow and broadcasts to cars running in the target broadcast area via base stations of RVC system. All cars equipped with RVC perform lane change control upon receiving this message.

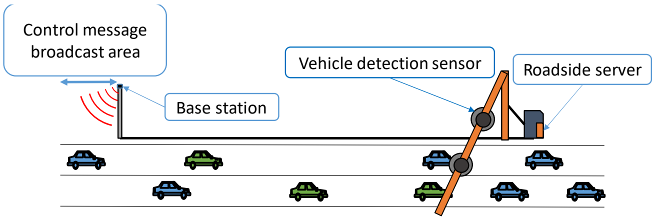


Fig. 1. Overall system configuration for applying the proposed scheme

For wireless system of RVC, we use ARIB-T109[8] operated in 700MHz band, whose communication range is approximately 1km at maximum.

The proposed scheme composes two types of controls, probabilistic forced lane change control and lane change restriction control as described below. Descriptions are based on the assumption that roads consist of two lanes.

a) Probabilistic forced lane change control

The roadside server calculates a forced lane change probability p, every T_u seconds using Eq.(1).

$$p = \frac{1}{2}\left(\frac{D_t}{F_L}\right) \tag{1}$$

$$F_s = min(F_1, F_2)\,, F_L = \max(F_1, F_2)$$
$$D_t = F_L - F_s$$

where F_1 is the traffic flow of a cruising lane, and F_2 is the traffic flow of a passing lane. D_t is referred to as traffic flow difference between lanes. The server periodically broadcasts a control message of forced lane change every T_u seconds which includes information of which lane is more congested and also the value of p. Cars which are equipped with RVC and running in the lane with more traffic flow try to move to the one with less traffic flow with the probability p upon receiving this message.

b) Lane change restriction control

Here, the server periodically broadcasts a control message every T_u seconds including information only regarding which lane is more congested. Then, cars running on the lane with less traffic flow refrain from changing its lane to the one with more traffic flow. Cars running on the lane with more traffic flow are allowed to change to the other lane according to their desired velocity.

Basically, probabilistic forced lane change control is applied before congestion occurs, and lane change restriction control is applied after congestion occurs. To detect occurrence of congestion, all cars equipped with RVC monitor their own velocity and notify the roadside server through RVC of the initial stage congestion when their own velocity have been less than the predetermined threshold V_{th} for time duration T_u. Upon receiving this notification from cars, the server changes control message to be broadcast from forced lane change control to lane change restriction control

The reason that probabilistic forced lane change control is applied before congestion occurs and lane change restriction control is applied after congestion occurs is as follows. In general, forced lane change control works effective when difference of average velocity between two lanes are small and also cars in the lane with less traffic flow run with large distance headway to their leading cars so that a car in the other lane can smoothly move into that space. Thus, forced lane change control should be applied before congestion occurs. In contrast, lane change restriction control works effective in the case that average velocity of each lane differs from each other, where cars in the lane with more traffic flow have lower average velocity than the other lane. This case occurs in the initial stage of congestion, just after some cars slow down in the uphill section. In this condition, many cars in the lane with more traffic flow try to change their lane. Since their velocity is lower than those in the other lane, they eventually reduce velocity of their following cars after changing their lane. Lane change restriction control avoids these phenomenon and improves overall average velocity. Thus, lane change restriction control should be applied after congestion begins, rather than before congestion.

IV. EVALUATION MODEL

Performance evaluation is conducted using the network simulator Scenargie[9]. The road model consists of two lanes with 5000m length and includes an uphill section. The uphill section starts at 1000m point and ends at 3400m points. The rest sections from 0 to 1000m points and from 3400m to 5000m point are flat. Each car leaves the starting point of the road model with velocity v_s and the time headway from the previous vehicle t_s according to the dataset shown in Fig. 2, which is collected by vehicle detectors at the bottom of the sag near the Yaita IC of Tohoku Expressway in Japan November 4th of 2006, when congestion occurs. Total number of cars is 774.

For the car following model, we use IDM+[10] that calculates acceleration by the following formula.

$$\frac{dv}{dt} = a \cdot min\left[1 - \left(\frac{v}{v_d}\right)^4, 1 - \left(\frac{s^*}{s}\right)^2\right] \tag{2}$$

$$s^* = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \tag{3}$$

Here, a : maximum acceleration[m/s^2], b : deceleration[m/s^2], v : current velocity[m/s], Δv : relative velocity to the leading vehicle, v_d : desired velocity[m/s], s : distance headway[m], s^* : desired distance headway[m], s_0 : minimum safe distance headway when stopped, T : minimum safe time headway[s].

In addition, each driver has different reaction time T_{reac}. These parameters are configured as shown in TABLE I.

There are three types of vehicles called type 1(controlled) and type 2(slow) cars, that are different in the behavior at the uphill. Type 1 cars do not slow down in the uphill section. In contrast, type 2 cars begin to decelerate with the constant deceleration of $0.294[m/s^2]$ corresponding to the gradient of the uphill. When their velocity decreased by more than 30km/h from the one at the beginnings of the uphill, they accelerate toward the desired velocity. Type 2 cars only exist among cars leaving the starting point of the road model from the time 500 sec to 600 sec. Only type 1 cars are equipped with RVC system, all of which perform the proposed control.

The ratio of type 1 and type 2 cars is set to 60% and 40% respectively. The type of each car is assigned randomly for satisfying this ratio. Since generally the performance evaluation results depend on the value of random seed, we use 15 different random seed for each given parameter set.

For performance comparison, the following three configurations of the proposed scheme are evaluated.

- Probabilistic forced lane change control is applied before the uphill section until congestion occurs, and no control is applied during congestion (Configuration(a))
- No control is applied before congestion occurs and lane change restriction control is applied in the uphill section during congestion (Configuration (b))
- Probabilistic forced lane change control is applied before the uphill section until congestion occurs, and lane change restriction control is applied in the uphill section during congestion (Configuration (c))

Parameters of the proposed control schemes are shown in Table II.

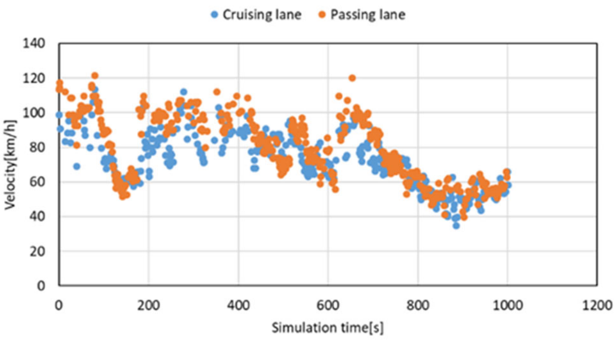


Fig. 2. Dataset of velocity and simulation time used for evaluation

TABLE I. PARAMETETERS OF THE CAR-FOLLOWING MODEL

A	0.45~0.75 m/s^2(random)
V	2.6~3.8 m/s^2(random)
s_0	1.65m
T	1 sec
Range of acceleration	Min. -5.0m/s Max. 3.0m/s
T_{reac}	0.54~0.74 sec(random)
Desired velocity v_d	90~100km/h(random) (For $v_s \leq 80$km/h) 100km/h (For 80km/h < v_s < 100km/h) v_s (For $v_s \geq$100km/h)

TABLE II. PARAMETERS OF CONTROL SCHEME

V_{th}	80[km/h]
T_U	10[sec]

TABLE III. LANE CHANGE WILLINGNESS

	P_{cp}	P_{pc}
Normal cars	0.5	0.1
Aggressive cars	1	1

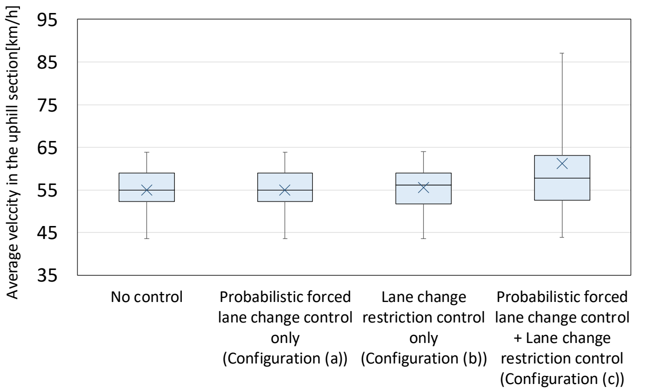
Type 2 cars and also type 1 cars during the time they do not receive messages from base stations of RVC freely perform lane changes for increasing velocity toward their desired velocity using algorithm presented in [11]. In this algorithm, lane change is allowed if distance headway of the car to a car running ahead and to a car running behind in the destination lane is larger than predetermined threshold which is specified according to relative speed between these cars. In addition to this algorithm, we set lane change willingness to each car, where it moves from the cruising lane to the passing lane with the probability P_{cp}, whereas it moves from the passing lane to the cruising lane with the probability P_{cp}. Values of P_{cp} and P_{pc} are shown in Table III. Ratio of normal cars and aggressive cars are 9:1, regardless of cars are type1 or type2

V. RESULTS

In this section, we show the results obtained from the simulations by applying the proposed scheme. As a performance metric, we mainly use velocity of cars running in the uphill section which is averaged throughout a simulation run.

A. *Comparison among different configurations of the control scheme*

Fig. 3 shows average velocity performance in the uphill section when applying three configurations of the proposed



scheme mentioned in Section III.

In general, traffic flow varies depending on positions of type 1 and type 2 cars in the road, which is decided by a random seed used in each simulation run while other parameters are fixed. Thus, average velocity of all cars is calculated for each simulation run and the graph is shown by box-whisker plots, representing distribution of average velocity values for 15 simulation runs. In terms of average value of box-whisker plot represented by a cross, configurations including lane change restriction control (aka, configuration (b) and (c)) work effective and configuration (c) achieves the largest improvement of average value. Upper quartile and lower quartile values are also the best when applying this configuration. In contrast, only applying forced lane change control in configuration (a) exhibits no improvement.

Fig. 3. Average velocity performance with varying configurations of the proposed scheme

Fig. 4 shows an example of time sequence of average velocity over elapsed time in a simulation run when applying configuration (b) and (c), and also when no control is applied. Without lane change control, average velocity begins to fall around 500s, when the first type 2 car appears, and falls to around 40km/h until 850s.On the other hand, when applying configuration (c) average velocity is maintained over 80km/h until around 800s and then reduces to 60km/h

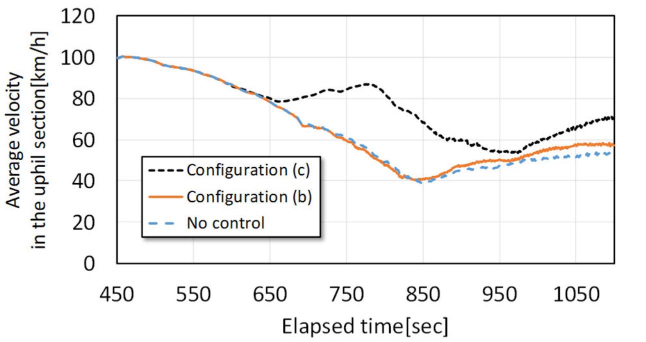


Fig. 4. Example of average velocity over elapsed time before and during congestion in configuration (b) and (c) of the proposed scheme

B. *Performance dependency on the area where lane change restriction control is applied*

Regarding configuration (c), we compare performance of lane change restriction control with changing target broadcast area from the server. Cars running outside this area do not conduct lane change restriction control during congestion. Here, we compare three types of broadcast area; i) Before the uphill section ii) In the uphill section iii) Both before and in the uphill section. Fig. 5 shows average velocity performance in each area setting. It shows that it gives the largest velocity when setting broadcast area only in the uphill section, in terms of average value and mean value of box plot. In this evaluation model, difference of velocity between two lanes occur from mainly two reasons. One is slow down of some cars in the uphill section, and the other is that target velocity of each car is different and slightly larger number of cars starting from the passing lane have larger starting velocity and also larger target velocity than those starting from the cruising lane as shown in Fig.2 and in configuration of Table I. Judging from the results of Fig.5, it can be estimated that difference of velocity between two lanes is significant particularly in the uphill section compared to other road sections, and thus applying lane change restriction control only in the uphill section is effective.

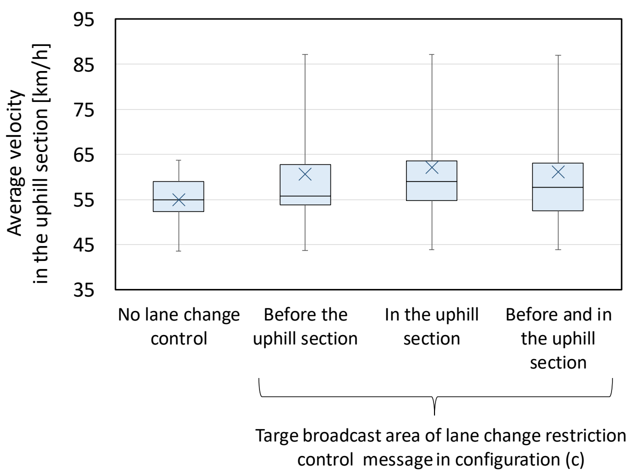


Fig. 5. Comparison of average velocity when applying lane change restriction control in different area

VI. Conclusion

This paper presented lane change control schemes named probabilistic forced lane change control and lane change restriction control for mitigating of congestion, which exploit road to vehicle communication.

Performance evaluation results have shown that a configuration to perform probabilistic forced lane change control before congestion occurs and to perform lane change restriction control during congestion brings better average velocity performance than other configurations in which only either of these controls is applied. Additionally, it was shown that lane change restriction control worked most effectively when it was applied in the uphill section. Lane change restriction control is estimated to work effective to avoid aggressive cars from frequently changing lanes in congested platoon which would lead to worse congestion.

As our future work, we plan to evaluate the schemes under different traffic flow patterns and confirm whether these results will hold.

References

[1] M. Koshi, M. Kuwahara, H. Akahane, "Capacity of sags and tunnels on Japanese motorways", ITE Journal, vol. 62, no. 5, pp. 17-22, 1992.

[2] E-NEXCO, “We analyze causes of congestion and implement countermeasures to solve congestion and mitigation” https://www.e-nexco.co.jp/en/activity/safety/detail_07.html , Accessed on July 29, 2019

[3] J. Xing , E. Muramatsu and T. Harayama, “Balance Lane Use with VMS to Mitigate Motorway Congestion”, International Jornal of Intelligent Transportation Systems Research, vol. 12, pp 26-35, 2014.

[4] Y. Saito, J. Xing, Y. Nonaka, T. Ishida, H. Uchiyama, “An experimental study on mitigation of expressway congestion with LED information board”, In Proceedings EASTS (CD-ROM), Vol.5, pp. 919–928 (2005)

[5] A. D. Patire, M. J. Cassidy, "Lane changing patterns of bane and benefit: Observations of an uphill expressway", Transportation Research Part B: Methodological, vol. 45, no. 4, pp. 656-666, 2011.

[6] W. J. Schakel, B. van Arem, “Improving Traffic Flow Efficiency by In-Car Advice on Lane, Speed, and Headway”, IEEE Transactions On Intelligent Transportation Systems, vol. 15, no. 4, 2014.

[7] Y. Zhang, P. A. Ioannou, “Coordinated Variable Speed Limit, Ramp Metering and Lane Change Control of Highway Traffic,” IFAC PapersOnLine Vol.50, issue 1 pp.5307–5312, July 2017.

[8] “700 MHz BAND INTELLIGENT TRANSPORT SYSTEMS”, https://www.arib.or.jp/english/html/overview/doc/5-STD-T109v1_2-E1.pdf, Accessed on November 11 2019.

[9] Scenargie, https://www.spacetime-eng.com/jp/, Accessed on August 1 2019.

[10] W.J. Schakel,, B. van Arem, and B. D. Netten, “Effects of Cooperative Adaptive Cruise Control on Traffic Flow Stability”, IEEE Annual Conference on Intelligent Transportation Systems(ITSC), Nov 2010.

[11] Ken Iwasaki, Kazufumi Suzuki, Koichi Sakai and Fumihiko Kanazawa, “The Understanding of Congestion Mitigation Effectiveness According to ACC-equipped Vehicles at Sag Section on Expressways,” Civil Engineering Journal, Man 2012.