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Variable Speed Limit to Improve Safety near Traffic Congestion on Urban Freeways

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Abstract—**Recently, the convergence of information technology with biotechnology, nano-technology, or other technologies has been creating a new paradigm. In the field of transportation, intelligent transport systems (ITSs) — a convergence of information technologies and transportation systems — have been studied. The VSL is one ITS technologies that aims to improve the safety and efficiency of transportation while controlling the speed limit according to traffic circumstances. Existing studies for VSL algorithms have considered only one station to control the traffic. However, it is not appropriate for an urban freeway to be installed with many stations. In this paper, a new VSL algorithm is proposed to enhance the effectiveness of VSL for multiple stations. It is based on the cooperation of stations and the real-time road information. The proposed algorithm consists of 4 steps: first is a "searching bottleneck station," second is a "calculating a size of congestion," third is a "calculating the number of controlled stations," fourth is a "calculating VSL." In our experiments, the microscopic traffic simulator VISSIM performed our modeling works. The results show that the proposed algorithm improves safety on roads with minimum additional travel time.**

I. INTRODUCTION

UBIQUITOUS worldwide advanced-information technologies, including computers and information communication systems, have been united with nano-, bio-, and other technologies. Convergence technologies have emerged from many contemporary working fields and have greatly impacted traditional human life patterns. Modern people cannot live in cities without transportation systems like cars, trains, aircraft, and so on. But the increasing use of automobiles causes traffic congestion on roads and results in increased travel times. To address these problems, physical approaches, like the extension of roads, have been suggested until now. However, such methods not only have high construction costs but also have physical limitations. Recently, ITS (Intelligent Transportation System) has been introduced to solve the problems of existing physical approaches. ITS aims not only to provide a low cost/high efficiency traffic system but also to enhance traffic safety on roads. ITS is based on the convergence of civil and IT technologies.

The VSL (Variable Speed Limitation) is one ITS technology. Since it controls the speed limit according to road traffic conditions, the safety and efficient usage of roads could be improved greatly. The VSL system is composed of stations, which are composed of the Dynamic Message Sign (DMS) displaying various traffic information and detectors sensing the traffic conditions. The current weather and traffic flow monitoring in real time also affects the ITS. For example, when rain or snow aggravates traffic, the VSL proposes a suitable speed limit according to current road conditions, assuring greater safety for drivers. In addition, due to accidents or a sudden influx of vehicles ahead, traffic congestion occurs on the freeway. Since the VSL controls the speed of vehicles entering these conditions, it could enhance safety and alleviate traffic congestion.

Existing studies on VSL have focused on a single-station environment. However, it is not appropriate for an urban freeway to be installed with many stations. In this paper, a new VSL algorithm is proposed based on the cooperative activities of multiple stations. It decides the VSL based on traffic velocity, density, and volume. To response to quickly changing traffic conditions, it collects traffic information per within 30 seconds in real time. The proposed algorithm consists of 4 steps: first is a "searching bottleneck station," second is a "calculating a size of congestion," third is a "calculating the number of controlled stations," which are the corresponding stations applied to the VSL, fourth is a "calculating VSL" for each station participating in the VSL. The aims of this algorithm not only improve road safety but also sustain the minimum increment in travel time. These effects can contribute to efficient road usage on urban freeways. In our experiments, the microscopic traffic simulator VISSIM is employed to construct a modeling traffic environment. The experiments show that the proposed algorithm provides improved safety with the minimum increase in travel time.

The remainder of this paper is organized as follows: Section two reviews work related to ITS and VSL. Section three describes simulation environments for experimental roads. Section four proposes a new VSL algorithm for multiple stations on an urban freeway. Section five offers measurement and evaluation of the performance of the proposed VSL algorithm. Section six concludes the paper.

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II. RELATED WORK

A. ITS

Automobiles provide convenience and fast transportation. Modern people cannot live in towns without transportation systems like cars, trains, aircraft, and so on. However, the increasing of automobiles causes the traffic congestion on roads. Travel time also increases according to traffic volume. To address these problems, physical approaches like the extension of roads have been chosen until now. However, method has not only high construction costs but also physical limitations due to unavailable ground space. Recently, ITS (Intelligent Transportation System) was introduced to solve traffic problems, instead of the existing physical approaches. As shown in Fig. 1, ITS is a convergence of IT, traffic, and road technologies. It applies the smart technologies of electronic, control, communication, and computer systems to existing road engineering, vehicle engineering, and signal systems in previous traffic networks. ITS supports safety, peace of mind, efficiency, and ecology for driving circumstances [1], [2].

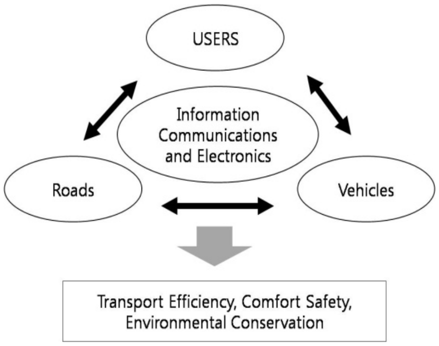


Fig. 1. ITS schema.

ITS is categorized as the road equipment aspect as well as the automobile aspect [3]. ITS is based on road equipment and has focused on applying suitable traffic control to drivers throughout some facilities. For example, variable speed limits, ramp metering control systems, and intersection-collision warning systems, and so on. ITS is based on providing drivers with automatic traffic information collected by the vehicle itself or by traffic facilities. Examples include, drowsy driver warning system, obstacle detection system, and optimal driving speed control system.

B. Variable Speed Limit

Traffic accidents on freeways have severe negative impacts on drivers and passengers. Many studies have looked at decreasing in traffic accidents on freeways to provide safe driving environments. One technology that can help with this is Variable Speed Limits (VSL). The VSL approach is different from existing methods that use fixed speed limits. The VSL system is comprised of three components. The first is the detector that monitors traffic circumstances. The second is the control system, which takes charge of storing and processing the data. The third is the DMS displaying the VSL. The stations are basic working units applying the VSL, composed of DMSs and Detectors. Previous research has reported that VSL technologies have improved the safety in traffic flow and decreased the stress of drivers. Many efforts have been made to apply VSL to other social fields.

When VSL is used in construction work on the freeway, it controls traffic congestion by providing the adaptive speed limit before cars enter the construction area. It greatly enhances safety and efficiency on roads suffering from traffic congestion [4], [5]. To improve safety on the freeway, VSL monitors traffic data in real time [6], [7]. Previous VSL researches have focused on traffic velocity, density, volumes, and, recently, weather conditions [9], [10]. Recent research has proposed a unified system applying the VSL and ramp-metering signal together.

To improve road safety, research [6] has introduced the concept of CP (Crash Potential) to the VSL algorithm. Based on CP values measured in real time, safety levels were calculated and the adaptive VSL was decided upon. Although this approach contributed to the safety improvement of VSL, it only reflected a single station in the VSL process. However, since freeways have moved to using multiple stations, these single-station results do not reflect the potential efficiency of VSL. In addition, this research regarded the ideal VSL period as from 5 to 10 minutes. However, these periods were too long to apply to the urban freeway, which requires fast responsibility in real time. If accidents or other severe traffic conditions create traffic congestion on the freeway, a VSL period of 5 to 10 minutes is enough to cause great traffic congestion. The research [7] also proposed the VSL algorithm on a single station, which did not consider the relationship between stations. To support the urban freeway with rapidly changing traffic states, a new VSL algorithm should be proposed, which must reflect the traffic cooperation of stations as well as real-time traffic monitoring.

III. EXPERIMENTAL ENVIRONMENT

A. Experimental Freeway

Fig. 2 shows the freeway environment used in our experiments, which represents the sections between Co Rd 42 to 113th St on I-35W NB in Minneapolis, Minnesota, USA. Many drivers use this section of the road for morning rush hour. Traffic congestion and accidents are frequent. This section has 11 entrance/exit gateways. There are two general lanes and one HOV (High Occupancy Vehicle) lane with a 65 miles/h speed limit. In these sections, detectors are employed every 1,200 ft ~ 2,600 ft and each station collects data for speed, density, and traffic flow every 30 seconds. Severe traffic congestion occurs between 6:00 AM and 9:00 AM when everyone is going to work. Traffic congestion frequently occurs in the Cliff Rd and TH12 WB areas. In particular, the entrance traffic at TH13 EB and the exit traffic at TH13WB causes bottlenecks. Upon encountering traffic congestion, the traffic delay phenomenon has affected the areas from Cliff Rd to Co Rd 42. During congestion, the speed of vehicles drops below 30 miles/h and drivers suffer frequent STOP and GO stages.

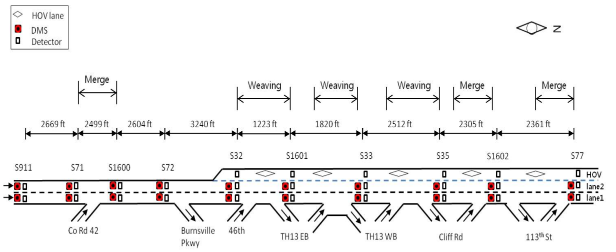


Fig. 2. Road I-35W NB.

B. *Simulation and Calibration*

To simulate the traffic environment on the freeway, we used a VSSIM simulator supported by PTV Corporation [11]. The VSSIM is a microscope simulator, which can be implemented and tested for various road environments. In addition, since it can support the COM interface, the simulator can be controlled by various computer languages like JAVA, C++, Python, and so on. For our experiments, we installed one DMS per station except the HOV lane in the road environment of Fig. 2. Only a few vehicles use the HOV lane so it does not have traffic congestion.

According to previous research [12], vehicles are usually driven at speeds of 4.9 miles/h ~ 9.9 miles/h higher than the speed limit. On I-35W, vehicle speeds have been measured at between 65 miles/h and 80 miles/h. The average speed is 70 miles/h, which is 5 miles/h higher than the speed limit of 65 miles/h. Therefore, our simulation designates the maximum speed as the speed limit plus 10 miles/h with 5 miles/h added to the average speed. For example, if the speed limit is 60 miles/h, the measured average speed is 65 miles/h with the maximum speed 70 miles/h and minimum speed 60 miles/h.

TABLE I
CALIBRATED PARAMETERS

Link Type	CC0	CC1	CC4/CC5	Waiting Time before Diffusion
Freeway	5.8 ft	1.0 s	-2.0/2.0	1 s
Merge	5.8 ft	1.0 s	-2.0/2.0	60 s
Weaving	5.8 ft	1.3 s	-2.0/2.0	60 s

Defaults: CC0=4.92 ft, CC1=0.9 s, CC4/CC5= -0.35/0.35, Waiting

To implement the traffic control system in the simulation environment, the calibration should first be applied. Without calibration, simulation results cannot reflect the real traffic environment on roads. In our experiment, we used vehicle-following behavior results, which were introduced by UC Berkeley [13]. In this paper, we categorized the road state as Freeway, Weaving, or Merge (see Fig. 2) and modified the CC values which are the component for controlling vehicle-following behavior in VISSIM. The adjusted CC values are CC0, CC1, CC4, CC5, and Waiting Time before Diffusion. Table I shows these values.

Fig. 3 shows the traffic at each station in both the simulations with calibration and the real roads. Fig. 4 shows the speed contour graphs. Fig. 4a shows the contour of speeds measured in real roads; Fig. 4b shows the default parameters of VSSIM; Fig. 4c shows the calibration parameters. As shown in these results, when using default parameters, no stations suffer from traffic congestion. However, in Fig. 4c, using the calibration parameters, both the starting time and ending time of traffic congestion are similar to those of real roads. Moreover, the periods of traffic congestion are similar too.

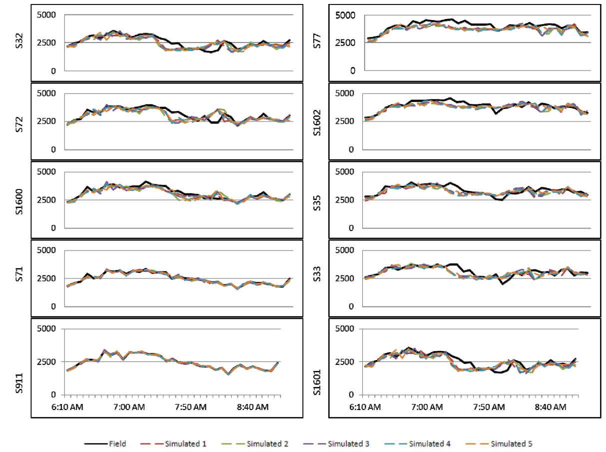
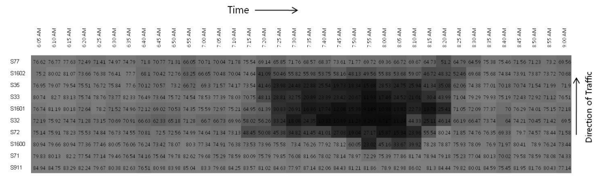
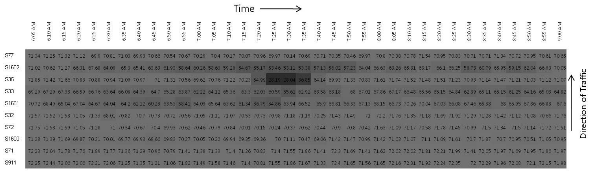


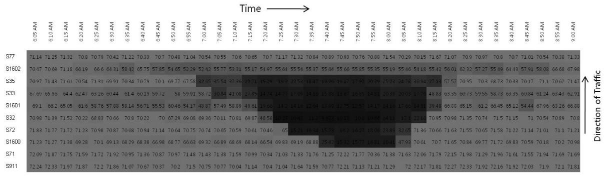
Fig. 3. Real traffic and calibrated simulation traffic.



(a) Real traffic



(b) Simulated traffic with default parameters



(c) Simulated traffic with calibration parameters

Fig. 4. Speed contour graphs in I-35W.

IV. VSL ALGORITHM

If vehicles are driven at different speeds on the freeway, serious accidents are possible. For examples, as shown in Fig. 5-(a), when the traffic congestion occurs in between station S_{j-2} and station S_j, the station S_j has abrupt speed drop when compared to previous stations. It makes these areas of station S_j get into dangerous section. Therefore, to secure safe driving environment, not only the sections with great speed differences are found but also the speed difference should be decreased gradually. However, to control the speed difference, if many stations are assigned with the low speed limit, which is below the existing fixed speed, the travel time increases and drivers have dissatisfaction. In this paper, we design a VSL algorithm considering these requirements, such as travel time and the number of stations participated in VSL.

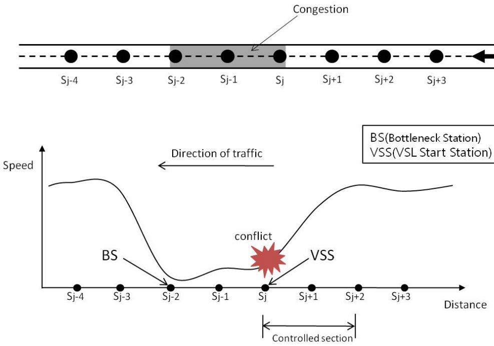


Fig. 5. Velocities stations.

To find traffic congestion, we have to decide the location of stations induced the traffic problem firstly. In this paper, the station ignited the traffic congestion is defined as BS (Bottleneck Station). A queue is made up with the stations successively affected by the traffic jam of the BS. The end station of queue is denoted as VSS (VSL Start Station). For example, as shown Fig. 5-(a), the stations from S_{j-2} to S_j suffer from traffic congestion. Since the station S_{j-2} is the origin of traffic congestion, the S_{j-2} is BS. The queue originated from the traffic congestion of BS is comprised of S_{j-2}, S_{j-1}, and S_j stations. In this example, the S_j is corresponding to VSS.

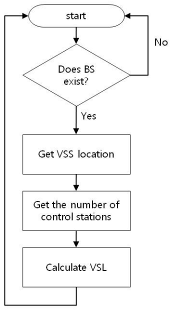


Fig. 6. VSL algorithm.

Fig. 6 shows the VSL algorithm, which is divided into 4 steps. Firstly, the BS is searching on current traffic flow. Second, the VSS position is checking up based on the BS information. Third is calculating the number of controlled stations based on the VSS. The Fourth is calculating VSL. This routine is repeated per 30 seconds. The 30-second checking is to respond quickly to traffic states instantaneously changing on freeway. However, the data like speed, density, and the volume of traffic are average data collected for past 1 minute. The reason is the fact that the collected data from real freeway are not always the right information. For example, the detector with currently high utilization cannot collect the traffic data of 100 % confidence. To alleviate these error rates, the VSL uses average data collected for past 1 minute.

The stations located in the upstream direction from VSS are defined as controlled section. In Fig. 5-(b), three stations are involved in the controlled section. In the third step of VSL, the number of stations controlled is calculated among stations involved in controlled section.

A. *Bottleneck Station (BS) Searching*

TABLE II
BS DECISION ALGORITHM

If $U_j \le U_{j+1}$ and $U_j \le U_{j+2}$ and $U_j <$ (*StaticSpeedLimit* – 5 miles/h) for 1min 30sec then BS = S_j

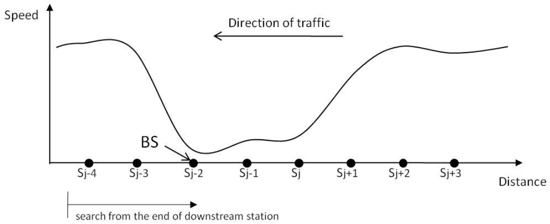


Fig. 7. BS location search.

The Table II shows the algorithm for detecting the BS, which cause the traffic congestion. In the Table II, U_j means the real measured speed of jth station and the *Static Speed Limit* variable represents the existing fixed speed limit. By applying this algorithm, we start the searching BS from the end of downstream station. For example, since the end of downstream station in Fig.7. is S_{j-4}, the algorithm searching BS is beginning on the S_{j-4} station. The speed of S_{j-4} is higher than that of S_{j-3} and S_{j-2}. The station S_{j-4} does not satisfy with both the first condition $U_j \le U_{j+1}$ and the second condition $U_j \le U_{j+2}$ proposed in the Table II. As a result, the station S_{j-4} cannot be BS. The S_{j-3} station also cannot be BS due to the same reason. However, the speed of S_{j-2} is lower than that of S_{j-1} and S_j. The first and second conditions in the Table II are satisfied. If the S_{j-2} sustains the current speed for 1 minute and 30 second, the last condition, $U_j <$ (*StaticSpeedLimit*-5 miles/h) for 1m 30, is also satisfied. Finally, the station S_{j-2} becomes BS. We introduce the last condition to eliminate the error data happened occasionally. For example, whenever detectors have malfunction and the current speed decreases for a moment due to exceptional circumstances, if the VSL is operated on unconditionally, the traffic flow could fall into disorder situation.

B. *VSL Start Station (VSS) Searching*

The VSS is the station encountering the high speed and the low speed. Table III shows the algorithm for searching VSS. In the Table III, U_j is the real speed measured in the station j. The algorithm starts the searching the VSS from the BS position to the upstream direction. For example, in Figure 8, the BS is S_{j-2} so the searching starts at S_{j-2}. If the speed of S_{j-1} is higher than that of S_{j-2} over the threshold value, the S_{j-2} becomes VSS. However, as pointed in the Table III, there is the restriction for deciding the threshold value. When the j^{th} station is inspected, the threshold value changes according to speed of $(j+1)^{th}$ station. Due to the restriction, S_{j-2} station cannot be VSS because both the speed of S_{j-2} and S_{j-1} are lower than Minimum VSL so the speed difference between these two stations cannot be higher than Minimum VSL value. The S_{j-1} does not become VSS as well, because the speed of S_j is lower than Minimum VSL value. It is the same reason.

TABLE III
VSS DECISION ALGORITHM

If $U_{j+1} - U_j >$ threshold *then* VSS = S_j
where
if $U_{j+1} >$ *Minimum VSL* then threshold = 10 miles/h
if $U_{j+1} \leq$ *Minimum VSL* then threshold = *Minimum VSL*

In the algorithm of Table III, we apply two restrictions in deciding the threshold value because the VSS is not found from the stations already placed on traffic congestion. For example, if the 10 miles/h speed is used as the threshold value, we have the next problem. In Figure 8, if the speed of S_{j-2} is 9 miles/h and that of S_{j-1} is 20 miles/h, the speed difference is 11 miles/h. So the S_{j-2} is selected as the VSS. However, since the S_{j-2} and S_{j-1} have the speeds of 9 miles/h and 20 miles/h individually, they are placed on the traffic congestion. Therefore, there are no reasons that we decrease the speed difference between these stations. As a result, the algorithm of Table 3 chooses the S_j as the VSS in Figure 8. The speed of S_j is lower than Minimum VSL but the speed of S_{j+1} is higher than the Minimum VSL. Therefore, the 10 miles/h is used as the threshold value. If the speed difference between these stations is over 10 miles/h, the S_j will become VSS.

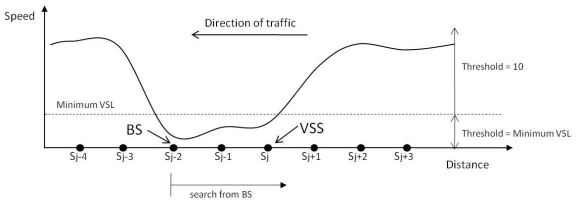


Fig. 8. VSS location search.

C. Number of Controlled Stations

After the VSS is decided, the number of stations is calculated based on the VSS. The selected stations participate in the VSL process to address traffic congestion. However, if many stations are placed on VSL control, the travel time may be increased unintentionally. Therefore, in our experience, the maximum number of VSL stations is three.

Fig. 9 shows the algorithm for deciding the stations controlled by VSL. The variable VSS-speed means the speed posted on the VSS station. The Shock-wave variable is the magnitude of impact stress due to traffic congestion, which is calculated based on VSS. The Speed-difference refers to the speed gaps between the VSS and the stations located "upstream".

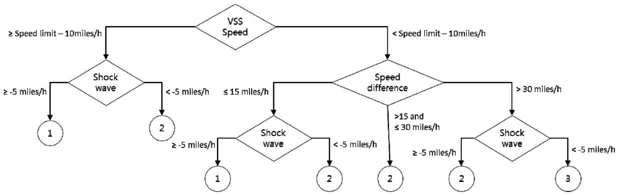


Fig. 9. Number of stations in VSL.

The algorithm of Fig. 9 is divided into two parts according to the value of the VSS-speed variable. If the VSS-speed does not drop lower than 10 miles/h less than the fixed speed limit, the speed differences between stations are trivial. In this condition, it is better to leave them without VSL, rather than using the VSL function. Therefore, the left edge of the VSS-speed variable diagram has a maximum of two stations, but the right edge has a maximum of three stations.

If the VSS-speed drops lower than 10 miles/h less than fixed speed limit, the algorithm examines the speed difference between the VSS and the stations located upstream. If the speed difference is great, the algorithm switches many stations to within the limits of possible participation in VSL control in order to attain the stepwise speed decrease. However, when the speed difference is small, only the minimum number of stations is involved in the VSL process, which induces both the stepwise speed decrease and the prevention of travel time increase.

$$\text{Shock wave } (SW_j) = (Q_d - Q_u) / (K_d - K_u) \qquad (1)$$

where

$$Q_u = (Q_j + Q_{j+1}) / 2$$
$$Q_d = (Q_{j-2} + Q_{j-1}) / 2$$
$$K_u = (K_j + K_{j+1}) / 2$$
$$K_d = (K_{j-2} + K_{j-1}) / 2$$

The final condition in this algorithm is the shock-wave condition. The magnitude of shock wave is driven from equation (1) where SW_j is the shock wave of j^{th} station. Q represents the volume of traffic and K represents the density of traffic at each station. The shock wave is used as follows: the degree of traffic congestion can be estimated according to whether the value of the shock wave is positive or negative. In addition, the magnitude of the shock wave is proportional to the alleviation or aggravation of traffic congestion.

D. Calculation of VSL

Based on the number of controlled stations, Fig. 10 shows three strategies used in VSL. Strategy-1 uses one station, strategy-2 uses two stations, and strategy-3 employs three stations.

Strategy-1 controls only one station that is designated as VSS. In the strategy, the VSL value given to VSS is the speed of the downstream station. For example, in Fig. 10, the VSL value of VSS S_j is the speed measured at station S_{j-1}. In Fig. 9, the cases corresponding to strategy-1 are marked as ①. They are driven from the following cases: if the speed of VSS does not drop lower than 10 miles/h less than fixed speed limit and the shock wave is positive, or if the speed of VSS drops lower than 10 miles/h, less than fixed speed limit, the speed difference is trivial, and the shock wave is positive. In these cases, traffic congestion does not occur so the VSL control does not need to reduce the speed difference between stations. The other case is if traffic congestion alleviates gradually. If traffic congestion is going to alleviate gradually, as the current speed of the downstream station is used, it will not permit the VSL to hinder the natural relaxation of the traffic congestion. In addition, as the speeds of stations downstream from the VSS are sustained, it can provide safety for vehicles.

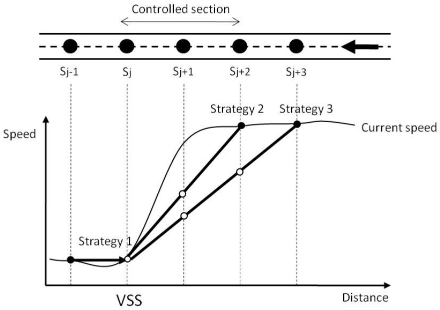


Fig. 10. VSL control strategies.

Strategy-2 and strategy-3 use the mid speeds of the two adjacent stations for VSL. For example, when strategy-2 is applied to the stations shown in Fig. 10, the S_j is VSS and it uses the speed of S_{j-1} as the VSL. The VSL of S_{j+1} is established as the median of the speeds at station S_j and stations S_{j+2}. In strategy-3, S_j is also the VSS and it uses the speed of stations S_{j-1} as the VSL. The VSL of station S_{j+1} and station S_{j+2} are assigned with the values trisecting the speed difference between station S_j and stations S_{j+3}. In Fig. 10, the small circles on the straight line of strategy-3 indicate the VSLs of S_{j+1} and S_{j+2}. Based on these stepwise speed reductions, the safety of vehicles can be improved because the speed differences between stations are minimal.

The upstream stations of VSS are categorized as controlled sections and the VSL is applied to them. Next, the downstream stations of VSS are also handled because they suffer from traffic congestion, which places the downstream stations of VSS in three possible situations. First, if the VSS has traffic congestion, they also suffer from the traffic congestion. Second, if the VSS has no traffic congestion, the traffic congestion does not appear in the downstream stations. Third, even if the VSS has traffic congestion, the downstream stations are normal, without traffic congestion. The third case occurs when the BS and the VSS are the same.

For all cases, as shown in Fig. 11, the best method is for each station to use the speed of its downstream station as the VSL. However, the stations applying the VSL located downstream of VSS represent the speeds below the maximum VSL. For example, in Fig. 11, the VSL is applied to station S_{j-3} because the speed of station S_{j-4} is over the maximum VSL. Based on these three approaches, the downstream stations of VSS could sustain the adaptive VSL, according to their traffic condition.

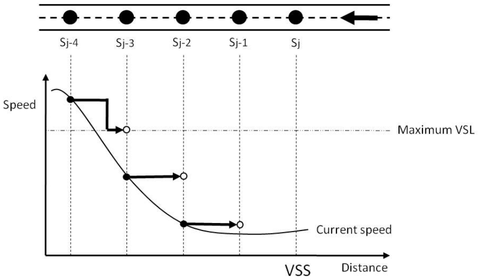


Fig. 11. Speed control on stations with VSS.

In the first and third case, the downstream stations of VSS suffer from traffic congestion or only the VSS does. In these situations, our approach effectively deals with the traffic congestion because it can quickly decrease the traffic volume in the traffic-congested sections according to the current freeway environment. The second case is that traffic congestion does not happen; since the drivers can see the speed of their previous stations, it contributes to road safety.

In this paper, since the VSL is calculated every 30 seconds, it is accounts for quickly changing freeway environments. However, since the 30–second readings also result in frequent speed variations, it induces confusion on the freeway. Therefore, whenever the current VSL varies, we designated two restrictions, as shown in Table IV. First, the VSL cannot decrease the speed of current station more than 10 miles/h at once. A speed reduction of more than 10 miles/h creates a shock wave in current traffic streams, which causes traffic congestion on the freeway. Second, the VSL can be increased up to 10 miles/h compared to the previous VSL and it can be decreased down to 5 miles/h. As the variation range is restricted, it prevents drivers from being confused by frequent changes in the speed limit.

TABLE IV
VSL CHANGING RESTRICTIONS

i. $U(j, t) - VSL(j, t) \leq 10$ miles/h
ii. *If* $VSL(j, t) > VSL(j, t-1)$ *then* $|VSL(j, t-1) - VSL(j, t)| \leq 10$ miles/h
else $|VSL(j, t-1) - VSL(j, t)| \leq 5$ miles/h

V. PERFORMANCE EVALUATION

A. Speed Variations

If the speed of vehicles varies greatly from station to station, they can be regarded as suffering from speed variations, which increases the possibility of accidents on the freeway. To evaluate the safety of the proposed VSL, we measured the speed variations on each station, as shown in Fig. 12. To compare accurate situations applying the VSL or not, we experienced speed variations on the corresponding stations for the period from the beginning time to the ending time of VSL.

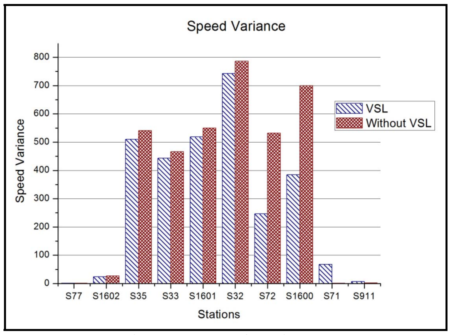


Fig. 12. Speed variance.

In our experience, all stations except station S71 represented a reduction of speed variations. The exceptional result of station S71 can be explained in Fig. 4c as the contour of speeds measured on real roads applying calibration parameters. The speeds at S71 show uniform distribution as being over 70 miles/h for the total simulation period. This means that traffic congestion in the BS location did not flow down to the S71 location. In this situation, without VSL, the speed distribution is close to 0. However, when the VSL is applied, the speed at S71 decreased by using VSL to reduce the speed difference between S1600 and S71. For this reason, the speed variation at S71 using VSL is higher than not using VSL.

However, all stations, except S71, preserve lower speed variations when the VSL is applied. In particular, S72 and S160 showed great reduction in speed variations. After traffic congestion began, these stations maintained great speed differences for a long time. In other words, these are the boundaries between the traffic congested areas and the normal traffic areas. If there is no VSL, these border areas are quite sensitive to traffic congestion. Even if traffic congestion increases minimally, their speeds decrease obviously. If traffic congestion is alleviated, their speeds increase immediately. However, when VSL is applied to these stations, since the speeds at upstream stations are adaptively controlled according to those of downstream stations, abrupt speed decreases or increases do not occur in freeway stations.

B. Travel Time

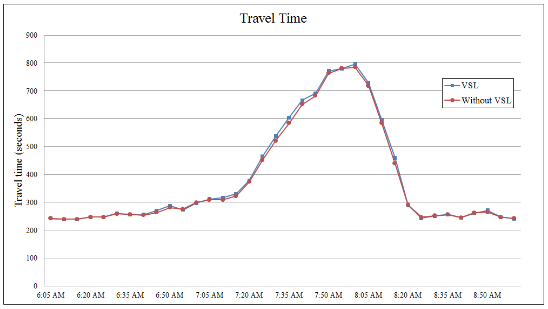


Fig. 13. Travel time.

Fig. 13 shows the travel times between S911 and S77 using VSL and not using VSL. The VSL aim is to enhance safety for drivers by adjusting the speed limit according to actual traffic conditions. However, if the VSL assigned is too low to support the safety of drivers or covers too-large areas, the increase of practical travel time is inevitable. Therefore, although the VSL improves the safety, the increase of travel time should be as minimal as possible. In Fig. 13, we can see that variations in travel time are almost equivalent in both the VSL and no VSL cases. Of course, small increases in travel time are found from 7:20 AM to 7:35 AM. This period is a traffic congestion time zone for work start times. However, the time increments are just below 10 seconds. From the experiment, we found that the increase of travel time was negligible.

C. Speed Difference between Stations

To enhance the safety of vehicles on the freeway, the speed difference between adjacent two stations should be small. Fig. 14 shows the maximum speed difference between two adjacent stations. Also shown in Fig. 14, the speed differences with VSL are smaller than those with no VSL. In particular, the VSL sustains small speed differences even in rush hour between 7:40 AM to 8:20 AM, which suffers from severe traffic congestion. In this time zone, the VSL case shows the speed differences between 30 miles/h and 40 miles/h. No VSL case shows the speed differences from 50 miles/h to 60 miles/h. From these results, we confirm that the VSL effectively reduces the speed differences between adjacent stations.

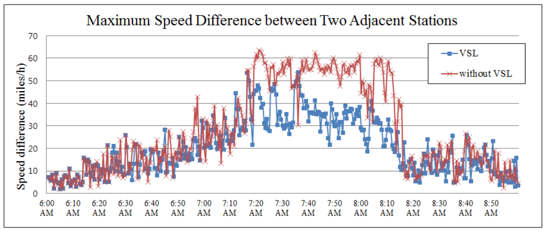


Fig. 14. Speed differences.

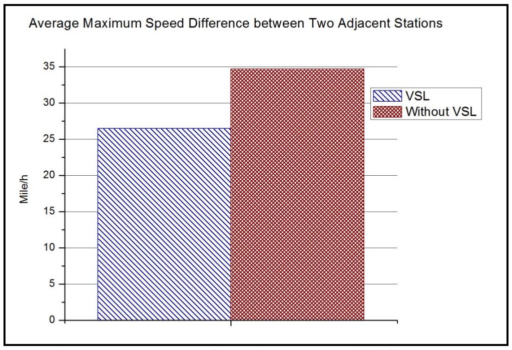


Fig. 15. Average of maximum speed differences.

Fig. 15 shows the average values of maximum speed differences between two stations for the total simulation period. The VSL case represents 25 miles/h and the no VSL case shows 35 miles/h speed differences.

D. Average Variations on VSL

VSSIM has a random seed item that makes slightly different traffic environments according to the designated random seed value. To measure the consistency of the VSL algorithm, we performed the simulations five times with dissimilar random seeds. Table V shows the average variations of three evaluation criteria mentioned the above sections for the five simulations. As shown in Table V, the speed variance reduced 14.2%, which was calculated as the average of speed variation from stations S911 to S77. The average maximum speed difference with VSL decreased 20.1%, compared to no VSL. The travel time increased 0.3%. From these results, we find that the proposed VSL algorithm does not show different results according to other randomly selected elements. In addition, the VSL algorithm enhances the safety of vehicles and shows a trivial increment in travel time.

TABLE V
AVERAGE VARIATIONS

Items	Variations (%)
Speed Variance	-14.2
Maximum Speed Difference between two adjacent stations	-20.1
Travel Time	0.3

VI. CONCLUSION AND FUTURE WORKS

In this paper, we proposed a new VSL algorithm based on the association of multiple stations on a freeway. The proposed method was composed of four steps. Its design aims are to enhance road safety with minimal increases in travel time. In our experiments, we confirmed that the speed variances were decreased and the speed differences between stations were also reduced. Based on these results, the road safety was improved. In addition, the increase of travel time was very trivial. To prove the consistency of our algorithm, we performed five simulations with different random seed values. The experiment results showed reductions of 14.2% in speed variance and 20.1% in average maximum speed difference between stations. In travel time, the ideal result would be no increase. In our experiments, a 0.3% increase in travel time was shown.

In our future work, we will study VSL algorithms on roads with many traffic lanes. In this case, the speed differences between the traffic lanes should be considered in the introducing the VSL. In addition, since the irregular distances between stations have meaningful impact on the existing VSL algorithm, we will develop a new VSL algorithm that reflects the distances between stations.

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