Abstract: Congestion of the freeway is caused by not only excessive demand for the mainline but also the influence of the exit ramp queue on the mainline. Actually, freeway congestion is largely generated by a mainline spillover of the exit ramp queue. Cause of the difficulties of building new and expanded roads in urban areas, Intelligent Transportation Systems (ITS) are essential to maximize the utilization of existing facilities such as Lane Control System (LCS), Ramp Metering, and Variable Speed Limit (VSL).

This study is aimed to study of traffic features of the expressway with exit ramp and develop the integrated model with VSL and exit ramp metering. First we explain the principles of exit ramp metering and VSL based on shockwave theory. Second we suggest integrated control model for the exit ramp using both VSL and exit ramp metering.

Key Words: Variable Speed Limit, Exit Ramp Metering, Shockwave theory, Freeway management

1. INTRODUCTION

Traffic congestion is a phenomenon caused when travel demand is greater than travel capacity. There are many reasons that cause the congestion. These days, freeway congestion is largely generated by spillover of the exit ramp queue. The queue in the exit ramp is affected by many factors such as geometric design of the road, the length of ramp and the hierarchy of the connected road. Especially when the exit ramp is directly connected to signalized intersection, the capacity of the ramp is determined by the green times. The exit ramp is designed to prevent the queue from exceeding the ramp storage capacity. But sometimes inefficient signal controls causes the residual queues and finally the queue of exit-ramp spills over into the mainline of freeway. To solve the mainline congestion caused by exit ramp queue, it is best solution to maximize the throughput in the exit ramp applying RMS or increasing the capacity of ramp. But considering the real condition such as the congestion of connected intersection or cost, there are some limitations to solve the congestion with only RMS. So in this paper, we study the combined solution applying the VSL (Variable Speed Limit) and RMS to solve the congestion caused by queue of exit ramp. VSL is one of the ITS techniques to improve the efficiency of freeways. The effects and the principle of VSL were verified by former studies (Papageorgiou, 2007; CHO, 2009) and this study is based on results.
of them.
In this study, we review the former studies and background issues about basic principles and the freeway control strategies. Second, we explain the effect of exit ramp metering based on signal control and VSL separately. The graphical solution based on time-space diagram and shockwave theory is used. And last, we suggest the RMS-VSL integrated control algorithm.

2. BACKGROUND ISSUES

The first background concerns fundamental diagrams, which refer to the correlation between the three variables [volume (q), speed (u), and density (k)] that describe the characteristics of traffic in an analysis of continuous traffic flow. The relationships between these variables can be represented in the following equation.

\[
q = \begin{cases} 
q_c & \text{if } k < k_c \\
q_0 & \text{if } k > k_{jam} 
\end{cases}
\]

\[
u = \begin{cases} 
\frac{\mu}{k} & \text{if } k < k_c \\
\frac{\mu}{k_{jam}} & \text{if } k > k_c 
\end{cases}
\]

\[
q = \begin{cases} 
qc & \text{if } k < k_c \\
qc & \text{if } k > k_{jam} 
\end{cases}
\]

Figure 1 Fundamental diagram

The volume-density diagram is divided into an uncongested state and a congested state. In an uncongested state, the volume increases as the density increases. In a congested state, the density increases but the volume decreases. When the speed is free, the density is 0 and the speed decreases as the density increases in the speed-density diagram. The volume-speed diagram shows the relationship of the speed to the volume, i.e., that the speed decreases as the volume increases in an uncongested condition and that the speed decreases as the volume decreases in a congested condition.

Under the upper theories, we explain the traffic features using shockwave theory. The theory of traffic shock-waves, first proposed by Lighthill and Whitham (1955) has been used in the analysis of bottlenecks and also traffic incidents such as an accident, a red signal light and a slow vehicle (Edie, 1975). The above analysis can be extended to determine the delays, and hence the costs, associated with such incidents.

A traffic stream may be described by its average flow \( q \) and average density \( k \) if stochastic effects are neglected. The velocity of a shock-wave that is created when the state of a traffic stream changes from \((q_i, k_i)\) to \((q_j, k_j)\) has been shown by Lighthill and Whitham (1955) to be

\[
w_g = \frac{q_j - q_i}{k_j - k_i}
\]

For forward and reverse shock-waves, \( w_g > 0 \) and \( w_g < 0 \) are respectively. If the points \( (q_i, k_i) \) and \( (q_j, k_j) \) are plotted on the \((q, k)\) diagram, the magnitude of the slope of the line joining \( i \)
and $J$ is represented by $|w_j|$. 

In the view of VSL, there have been many studies about freeway management technique, especially VSL. Most of them are about modeling and evaluating the VSL strategies or case studies focused on safety. But there are only few studies about the principle of VSL theoretically and the effect to the traffic features. One of them is the study of Papageorgiou (2007). Papageorgiou studied the change of volume and density when VSL was applied. In his study, VSL decreases the slope of the flow-occupancy diagram at below-critical conditions; shifts the critical occupancy to higher values; and enables higher flows at the same occupancy values in overcritical conditions. For example, no-VSL data in the critical occupancy area are more likely to correspond to non-congested conditions, whereas 40mph-VSL data in the same area are likely to correspond to overcritical traffic conditions, simply because a 40mph VSL is usually not imposed in below-critical traffic conditions. Looking at related researches about the principle of VSL conducted in Korea, J. Park (2009) analyzed the operational effect of a VSL when the capacity is reduced by 50% due to accidents, and explained it using the traffic flow model and the shockwave theory. In this research, when a VSL of 60 km/h is imposed from free flow speed 100 km/h, the speed of backward queue would be delayed. As a result, it is found that the effect of VSL was explained by the change of the total delay with VSL. In the research of H. Cho (2009), J. Lee (2010), the rule of VSL is described in more detail. They try to explain how VSL changes the state of traffic feature using the time-headway and distance-headway and convert the result to the volume-density relationship. They suggest VSL model applying Supply-Demand method based on Cell Transmission model and verify the effect of VSL numerically.

![Figure 2 Changes of traffic feature and shockwaves when the capacity decrease without VSL](image1)

![Figure 3 Changes of traffic feature and shockwaves when the capacity decrease with VSL](image2)
3. METHODOLOGY

Most of all, like all other continuum traffic flow models, vehicles in this study are treated as fluids. The advancement of flow from one segment to another is governed by flow conservation rules, supplemented by an assumed flow-density relationship. And we apply the Newell’s Simplified Traffic Flow Theory for easier calculation and application. The main method is both IT model and the graphical solution based on shock wave theory. The basic assumptions of traffic condition are the same as Table 1. Others are as follows;

Table 1 : Layout for main analysis

<table>
<thead>
<tr>
<th>Road layout</th>
<th>details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20km of three lane one-way freeway</td>
</tr>
<tr>
<td></td>
<td>Main segment of freeway with an exit ramp</td>
</tr>
<tr>
<td></td>
<td>all lanes for vehicles to go through and the only the last lane is for exit vehicles</td>
</tr>
<tr>
<td></td>
<td>Exit ramp is connected to a two-one-way signal intersection with two phases</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Traffic condition</th>
<th>details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Only 100% passenger cars are considered</td>
</tr>
<tr>
<td></td>
<td>No acceleration/deceleration</td>
</tr>
<tr>
<td></td>
<td>Full compliance with the VSL and traffic signal</td>
</tr>
<tr>
<td></td>
<td>Left/right turns are forbidden in this intersection</td>
</tr>
<tr>
<td></td>
<td>Cycle length are fixed.</td>
</tr>
</tbody>
</table>

To suggest the integrated control model, we check the effect of three cases. First is exit ramp metering by signal control and second, VSL separately and the last is the case of applying both control strategies at the same time. The basic concept of VSL is from the changes of shockwave by VSL in Cho’s former research. The shockwave of exit ramp metering by signal control is as follows.

The intersection is two one-way streets and requires two phases to accommodate two competing traffic demand, one of which is from exit ramp. The intersection is two one-way streets and requires two phases to accommodate two competing traffic demand, one of which is from exit ramp. Green splits are determined by the ratio of two demands as follows

\[
\phi_{EB} = C \times \frac{q_{EB}}{q_{EB} + q_{NB}}, \quad \phi_{NB} = C \times \frac{q_{NB}}{q_{EB} + q_{NB}}
\]

where, \(C\) : cycle length

\(\phi_{EB}, \phi_{NB}\) : green splits

\(q_{EB}, q_{NB}\) : saturation flow rate (demand) of each approach

To optimize splits of the intersection, the time-space diagram is drawn for the two approaches at the end of each cycle using shockwave theory. Figure 6 shows the fundamental diagram of volume-density of this intersection and the time-space diagram of the eastbound approach which is connected to exit ramp. \(q_e\) is the saturation flow rate of this intersection and \(q_{EB}\) is the flow rate in the green time from eastbound. When vehicles are approaching the intersection as the speed \(u_f\) and waiting during the red time, the traffic feature changes from A to B in the left fundamental diagram. Traffic queue will develop as the speed \(w_g\) when the signal is red and the queue will start to discharge as the speed \(w_e\) at the start of green time. In this case, maximum queue is \(X(a)\). If the green times of all approach are adequate to accommodate all incoming traffic, all of the waiting vehicles can pass during green time and there are no residual queues at the end of the cycle. In case of exit ramp, the queue length is compared the maximum length of ramp as the waiting area of exit flow. If the residual
queues are left continuously, the length of queue in ramp increases. When the length of queue exceeds the ramp storage capacity, finally the queue of exit-ramp will spill over into the mainline of freeway as the Fig 5.

![Figure 4 Shockwaves with signal control](image)

Figure 4  Shockwaves with signal control

![Figure 5 Spillover into the mainline of freeway because of residual queue](image)

Figure 5  Spillover into the mainline of freeway because of residual queue

Note the application of the VSL in this exit ramp connected to the signal controlled intersection. As stated in the part 2, the application of VSL upstream of a bottleneck that is close to becoming active, will temporarily decrease the mainstream flow arriving in the bottleneck area, thus delaying the bottleneck activation and the resulting congestion. As the Fig 6, the speed of formation of queue is controlled as the speed and the congestion of the exit ramp will be reduced than the case of no-VSL. In Fig. 7, we can find that the queue length is dissipated and smaller than the maximum length of exit ramp at the second cycle length.

![Figure 6 Shockwaves with Signal-VSL control](image)

Figure 6  Shockwaves with Signal-VSL control
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