

Article

Driving Behavior Characteristics of Merging Sections in the Urban Underground Road Junction: A Driving Simulator Study

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Abstract: This study aims to investigate left- and right-side merging sections on urban underground roads based on virtual reality driving simulator experiments. The behaviors investigated were changed by acceleration lane in the merging section, including 100, 120, and 140 m, considering current design guidelines. Typically, lane changing behavior was studied based on experiments using speed and lateral placement on driving. The behavior of more speed reduction in merging sections occurred in left-side merging than in right-side merging sections. In the left-side merging sections, speed reduction and acceleration rate decreased with the length of the acceleration lane. In the cases with relatively long acceleration lanes, lane changing locations for left-side merging sections were more sensitive than those of right-side merging sections. Some results from the driving simulator experiments show that road geometric design based on left-side merging sections might have more risk situations due to driver expectation and behaviors. This article provides technical knowledge to be applied to the acceleration lanes of left-side merging sections that extend 1.4 times longer than the usual road designs.

Keywords: urban underground road junction; left-side merging sections; double-deck tunnel; driving simulator; driving behavior



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1. Introduction

There is chronic traffic congestion in metropolitan areas throughout the world due to high population density and an increase in car ownership. Considering complex land use and over-saturated above-ground spaces, the current focus has been on providing roads to underground spaces to solve urban transportation issues. Underground roads are already being constructed and operated in many major cities around the world. Examples include the Central Tunnel in Boston, the A86 West Tunnel in Paris, the M30 Tunnel in Madrid, the Cross City Tunnel in Sydney, Airport Link Tunnel and the Clem Jones Tunnel in Brisbane, the Yamate Tunnel in Tokyo, and the Bund Tunnel in Shanghai [1]. Previous studies have shown that the use of urban underground space (UUS) can promote sustainable urban development [2,3]. UUS can improve the resilience of urban spaces [4] and can contribute to the development of livable cities [5,6]. Utilizing underground space for the purpose of dealing with urban and transportation problems is a continuing trend in urban development over the past few decades [7]. Ref. [8] found that underground roads reduce traffic aboveground, improve road networks, free up land use changes for redevelopment, provide opportunities for landscape preservation, reduce greenhouse gas emissions, and protect against inclement weather. Thus, the construction of underground roads in UUS contributes to the sustainable development of urban transportation. In this context, a deep urban underground road (UUR) that extends more than 40 m beneath ground level has recently come to be one of Korea's most important road issues. It was planned for the Shinwol–Yeoui UUR to begin operations in 2021, as well as the Seobu UUR, which

were constructed sequentially to alleviate the ongoing traffic congestion in large cities and disconnection of urban areas due to existing freeways or expressways, and to provide open space for users. Additionally, UUR construction projects, especially in the metropolitan area of Korea and Busan, the second largest city in Korea, are constantly being planned and promoted.

Unlike in the past, tunnel technology for UUS construction has advanced rapidly. As the demand for underground road infrastructure in cities increases, more complex underground road infrastructure will be developed in the future to improve some of the urban traffic problems. According to [9], complex underground roads for automobiles have multiple connections to the ground road network, and there must be the possibility of interconnectivity between adjacent UURs. It is necessary to implement a network-based underground traffic system within the UUS, rather than a link-based system. In contrast to this, the underground roads that we still experience around the world include those that flow into and out of the ground only at the starting and ending points, as well as those that diverge or merge in the middle of the main line and connect to the ground road network [10]. Urban road construction must evolve to underground routes due to land use restrictions in urban areas. Consequently, urban interchanges and underground roads are now being constructed and utilized. In this context, it is expected that two underground roads will intersect in the UUS, forming a junction that will allow traffic from all directions in the long run [11]. However, there is almost no technical review or research on UUR junction design worldwide at the moment. The underground road design guidelines that we can confirm apply the design standards established for existing roads to underground roads for many design factors and refer to considering additional safety margins for major design factors such as radius and sight distance. It has been noted that unstable driving behavior exhibited by drivers under constraints such as spatial closures is not sufficiently considered when designing underground roads.

Accordingly, to prevent traffic accidents due to human errors at UUR junctions of network-type underground infrastructure soon, research is needed on the application of geometric design factors that take driving behavior into consideration. In this study, we analyzed driver driving behavior by modifying key design factors of the ramp terminal by setting the geometric shape of the UUR junction. To accomplish this, we constructed a virtual reality (VR) environment for the UUR junction and conducted an experiment using a driving simulator. It should be noted here that the scope of this study focused on the merging sections of the on-ramp terminals at UUR junctions, where visibility was limited by the tunnel wall and more attention was required by drivers.

2. Literature Review

2.1. Driving Simulator Studies in Tunnel Environments

More than 70% of Korea's land area consists of mountains, so tunnels are required to overcome topographical challenges. These tunnels are gradually becoming longer due to topographical constraints. It is generally accepted that drivers in tunnel environments experience psychological effects, such as anxiety. Several papers and research reports have described the unstable driving behavior caused by this problem [12–14]. Due to the difficulty of collecting data in an actual tunnel environment for the analysis of driving behavior, many studies have carried out VR experiments using a driving simulator. Previous studies using naturalistic and driving simulators have confirmed that drivers perform differently inside road tunnels, with significant differences in longitudinal speeds, acceleration or deceleration, and lateral placement recorded along the tunnel scenario as compared with the control scenario, which has similar road geometries and alignments to the first but does not contain tunnels [15].

An underground road is the same as the tunnel we are familiar with, in that it is an underground road enclosed by walls. Because of its restricted environment, underground roads differ significantly from general ground roads in terms of their driving environment. In comparison with ground roads, there has been little research on alignment design

indicators for underground roads, and designers do not have access to separate design standards to refer to when designing [16]. However, underground roads with diverging or merging traffic have different driving characteristics than those that simply connect a starting point with an ending point. Research related to underground roads has so far primarily focused on driver behavior on the main line, and there has been little research on driving behavior and geometrical factors influencing safe design at ramp terminals. These are recent studies of underground roads with ramp terminals that we may reference. To study the characteristics of vehicle operation in an underground road under different ramp entrance conditions, an experimental design was used. It has been shown that ramp layout and the mainline traffic environment have significant effects on the characteristics of vehicle operation [17]. A study evaluating the effectiveness of traffic signs applied to ramp terminals of underground roads has also been conducted [18]. In this context, this study differentiates itself from other studies as a study that analyzes driver behavior at merging sections of on-ramp terminals within UUR junctions based on VR environments.

2.2. Driving Behavior and Major Design Factor of Ramp Terminals in UUR

The ramp terminal is a road geometry environment in which driving decisions are made regarding a series of processes including traffic situation recognition such as gap acceptance, speed control, and lane changes in a relatively short distance [19]. In this road environment, drivers are expected to behave differently depending on whether they exit or enter the main line. A vehicle driving on the main line changes to the deceleration lane in diverging sections of off-ramp terminals and consistently decelerates to the ramp's speed limit level. As opposed to this, the vehicle driving on the ramp generally recognizes the vehicle driving on the main line in merging sections of on-ramp terminals, accelerates as close as possible to the main line's speed in the acceleration lane, and changes lanes to enter the main line at the same time. The speed difference between vehicles exiting and entering the main line and those on the main line not only increases the risk of accidents but is also difficult to handle once accidents have occurred [20]. Thus, drivers may be required to be more careful while driving on a ramp terminal than they would be on a main line with normal alignment.

A growing amount of attention has also been paid to ensuring traffic safety in diverging and merging sections of UURs [21]. The ramp terminals of UUR have a similar environment as those of ground roads in terms of road alignments; however, tunnel walls may make it more difficult for drivers to recognize traffic conditions or change lanes. Unlike ground roads, in merging sections of on-ramp terminals within UURs, drivers on the ramp and those on the main line cannot be identified with each other due to the tunnel wall. In other words, it is a road environment in which a driver's visibility is restricted. As soon as the driver enters the large-section tunnel, mutual recognition is possible between the main line and ramp drivers. In such an environment, if a driver trying to merge on-ramp fails to recognize and react at the right time to vehicles driving on the main line, rapid deceleration or acceleration may occur in the acceleration lane, increasing the risk of an accident.

Meanwhile, UUR junctions, including ramp terminals, where driver safety must be ensured, as mentioned above, are significant traffic facilities for which appropriate geometric forms and design standards must be applied during the planning and design process. There are, however, very few UUR design guidelines that describe these matters in detail worldwide. According to related research, [22] suggested that the shape of the underground road junction should allow left-side entry or exit as well as right-side in some situations in which the size of the underground space must be minimized, and since drivers cannot guess what form the ramps forming the junction are connected to, acceleration lanes should be designed so that vehicles driving on the ramps can sufficiently identify those driving on the main line. Also, an acceleration lane should be designed at an appropriate length to enable the driver to reach a sufficient speed. In an analysis of traffic behavior, it was revealed that merging speed depends on both ramp geometry and speed-change lane geometry. Lower merging speeds were associated with higher collision rates in acceleration

lanes [23]. Additionally, the direction of connection at the merging sections is related to the driver's behavior when changing lanes in the acceleration lane. It is found that for the ground road case where either the leading or the following vehicle is present in the main line during merging movements, a merging starting position of 50% to 60% of the merging section on a right-side ramp corresponds to a safe situation; in contrast, a left-side ramp with a merging starting position of 30% to 40% is an unsafe situation [24]. This means that even in merging sections of on-ramp terminals at UUR junctions, driving behavior may vary depending on the direction of the ramp.

3. Methodology

3.1. UUR Junction Based on Double-Deck Tunnels and Left-Side Merging Sections

A UUR junction formed by two underground roads intersecting three-dimensionally in a UUS can result in very high construction costs if the junction is designed inefficiently. In Korea, most UURs, which are already in operation or being planned, are parallel tunnels placed side by side with a minimum gap between each tunnel. Traffic flows are separated in each direction. As a result, it eliminates the risk of accidents caused by crossing the center line on roads. It also has the advantage of relatively low construction costs compared to one large-section tunnel for two-way traffic flows. The parallel tunnel does not pose a major obstacle when it simply connects the ground and the underground; however, it is not suitable for forming a junction that would allow traffic to flow in all directions between two parallel tunnels in the UUS. This is because the length of a semi-direct ramp between two parallel tunnels may be quite long. Thus, a UUR junction should be designed with double-decker tunnels instead of parallel tunnels to allow traffic to move in all directions.

A double-decker tunnel is defined as single-tube tunnel where one carriageway is located above the other [9]. On the upper and lower carriageways, traffic flows in opposite directions. A schematic shape of a UUR junction is shown in Figure 1, when two double-decker tunnels intersect, connecting four right direct ramps and four left direct ramps each. Here, it is possible to design it as a single-tube tunnel by connecting ramps 1 and 8 between the upper floors, and ramps 4 and 5 between the lower floors. In contrast, ramps 2 and 6 connect from the upper to the lower floors, while ramps 3 and 7 connect from the lower to the upper floors, so each tunnel must be designed independently. In this way, separate sections with four diverging sections of the off-ramp terminals and four merging sections of the on-ramp terminals are formed.

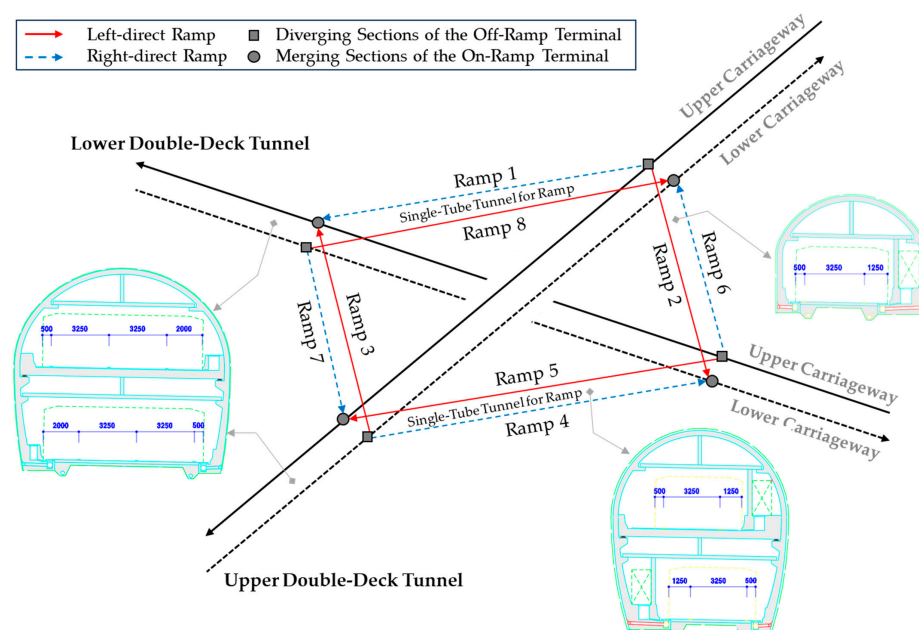


Figure 1. Schematic shape of a UUR junction.

UUR junctions based on a double-decker tunnel inevitably form left-side merging sections. In many countries around the world, such as Korea, the United States, France, Spain, etc., vehicles drive on the right side of the road. The driver's seat is positioned on the left side of the vehicle. Generally, these countries stipulate or recommend that when entering or exiting a major arterial, such as a freeway or expressway, the ramp must be connected on the right side. When changing lanes in a left-side merging section, drivers must turn their heads more to the right-side mirror to keep an eye out for approaching vehicles to the right. The difference in physical behavior required between left-side and right-side merging sections is a major factor affecting a driver's safety. It is anticipated that this factor will have a greater impact on driver behavior and safety in merging sections of tunnel environments. Ref. [25] found that accidents occurred about 7.88 times more often in the left-side merge than in the right-side merge based on the model results, assuming a negative binomial distribution on generalized linear models, built from a case study on the crash frequency of I-75 through downtown Dayton, Ohio. Also, as noted in Korea's road design guidelines, the left-side ramp terminals have a higher accident rate than the right-side ramp terminals, and the left-side ramp terminals should be avoided whenever possible.

However, major countries around the world that have underground infrastructure are already operating underground roads designed with a left-side direct ramp, such as the A86 in Paris, the M30 in Madrid, and the Big Dig in Boston. To create a safe traffic environment at UUR junctions in the future, a safer design of the left-side on-ramp terminals is necessary. To do so, many studies reviewing driving behavior and design factors are required. Hence, in this study, we conducted a VR driving experiment by setting the scenarios according to the length of the acceleration lane, which is a major design factor, to compare driving behavior in left-side merging sections and right-side merging sections. To conduct this study, a VR driving environment was set up. Figure 2 illustrates the geometry of merging sections of on-ramps.

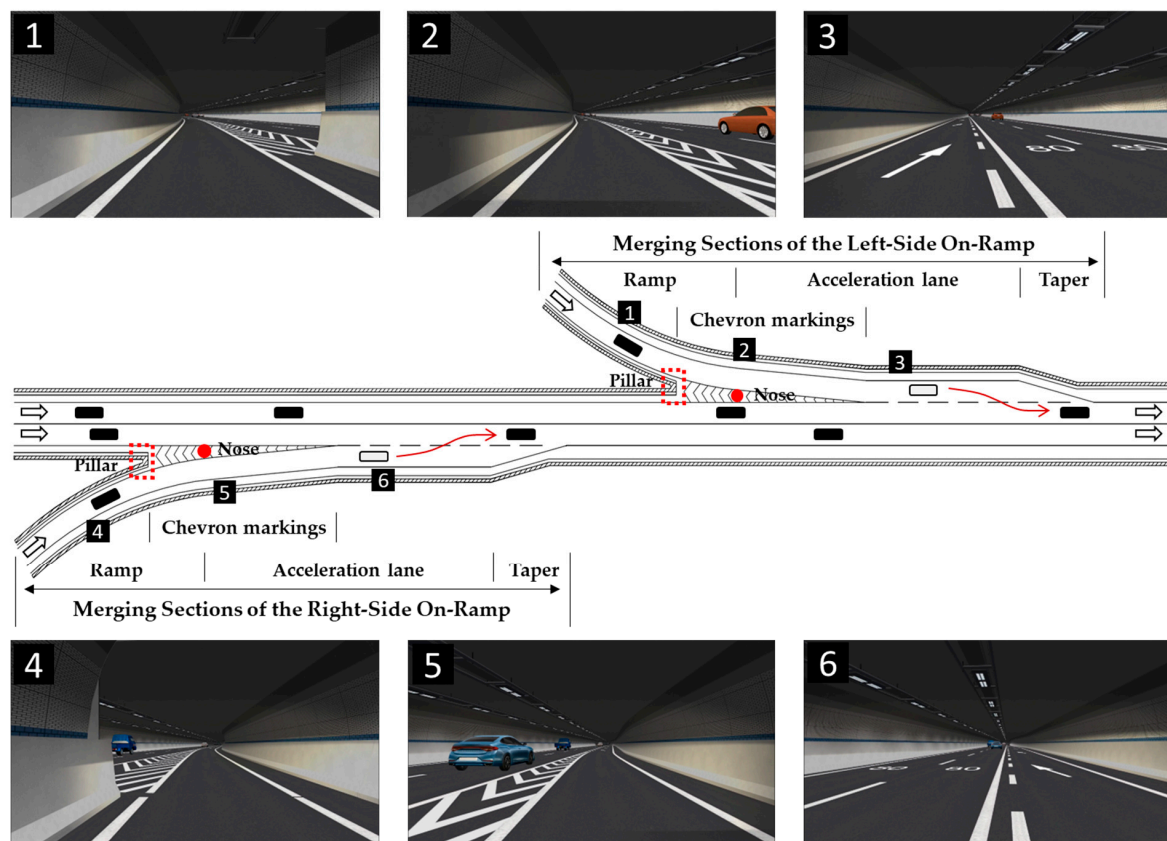


Figure 2. Geometry of on-ramp merging sections in a UUR junction.

3.2. Driving Simulator Experiments

We conducted a VR driving experiment using a driving simulator (DS) owned by the University of Seoul in Korea. A DS is an experimental device designed to record driving data in a VR driving environment that allows drivers to feel as if they are driving on a real road so they can conduct research that would otherwise be difficult to conduct in a field experiment. To create the VR driving environment, we used UC-win/Road ver. 15, made by Forum 8 in Japan, a 3D virtual reality software that can implement the road driving environment professionally. This software, synchronized with a DS, can extract driving behavior data, including speed, lateral placement, brake power, and steering angle. Figure 3 shows a VR driving experiment using a DS on underground roads.

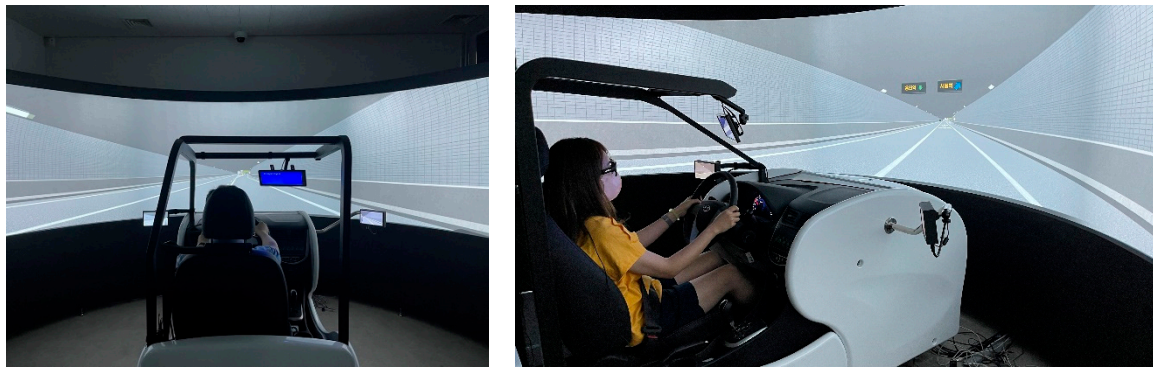


Figure 3. Driving simulator with UC-win/Road.

A VR driving environment for a double-deck tunnel was created using Korea's UUR design standards. So, we created a VR driving environment consisting of a simple network that includes ramp terminals that connect the two double-deck tunnels. Considering that this road environment is a UUR, it was assumed that only small cars would be permitted, and the facility limit accordingly was 3.3 m. The design speed of the main lines was set at 80 km/h, the design speed of the ramps to 50 km/h, and the lane width to 3.25 m. As the design level of service for Korea's UURs is generally set at LOS D, the main line of the VR driving environment was maintained at 1200 vehicles per hour per lane.

This study used experimental scenarios in which the length of the acceleration lane was varied as an experimental factor to compare driving behavior at the merging section based on the acceleration lane. According to the direction of merging into the main line, we divided it into right-side and left-side merging scenarios. Design specifications for the left-side and right-side on-ramp terminals were applied equally. The length of the acceleration lane was set at 100 m, which is the minimum design standard in Korea when the design speed of the main line is 80 km/h and the design speed of the ramp is 50 km/h. Also, to compare driving behavior, acceleration lanes with lengths of 120 m and 140 m were set as additional scenarios. The 20 m interval is determined by applying a larger design margin to 13.89 m per second converted from a ramp design speed of 50 km/h. In all scenarios, the taper at 60 m was applied equally. As a result, six experimental scenarios were set up based on the length of the acceleration lane and the direction of merging into the main line. Each scenario was named RS100, LS100, RS120, LS120, RS140, and RS140.

The main experiment for the VR driving experiment was conducted from April 17 to April 27 in 2022. Participants were recruited from among people with a driver's license who drove regularly and had at least two years' experience driving, and those working in the transportation industry were excluded. A total of 35 participants were recruited in the VR driving experiment, with 7 in their 20s (3 males/4 females), 9 in their 30s (5 males/4 females), 9 in their 40s (5 males/4 females), and 10 in their 50s (5 males/5 females). The participants were instructed to drive while observing road signs and speed signs based on their own driving experience. In addition, to ensure that the participants adapted fully to the DS device, they were asked to run a pre-test for approximately five minutes before

the main experiment. After that, the main experiment was conducted for approximately 25 min. All these processes were conducted under the supervision of the experimenter.

3.3. Analytical Indicators

Several studies have suggested that speed and lateral placement (LPM) are useful indicators of safe driving [26–28]. So, in this study, speed and LPM were used as driving log data that can be obtained through virtual driving experiments, and speed changes and points of lane change were used as indicators to explain driving behavior in the merging sections. Driving behavior in merging sections can be explained in general by the gap acceptance theory. The ramp vehicle driver is believed to accelerate and merge directly if the immediately available “gap structure” is acceptable. In cases where no gap is immediately available, however, the driver can either accelerate to create a merger opportunity or decelerate and wait for an acceptable gap later [19]. It is not a problem for the driver to accelerate and merge immediately, but if the driver slows down, there is a high risk that the driver will accelerate rapidly in the remaining section of the acceleration lane [29]. In this case, the deceleration and point of lowest speed in the merging section may differ from one driver to another. Looking in the side mirror, the ramp driver’s perception of relative speed in relation to the adjacent vehicle driving on the main line varies for every driver. It is difficult to accurately reflect that speed in analysis.

In this regard, the speeds at four points in the merging section were extracted to effectively explain the differences in driving behavior between all scenarios. Figure 4 illustrates the outline of an analysis of driving behavior in the merging sections. First, S_{entry} is the speed of passing through the physical nose, the pillar. Second, S_{min} is the minimum speed in the merging section, including the chevron markings and the acceleration lane. Third, S_{lc} is the speed at the lane changing location. Finally, S_{exit} is the speed at the end of the taper in the merging section. Then, we set up Equations (1)–(3) as analysis indicators as follows. Equation (1) refers to the speed difference, $S_{difference}$, between S_{entry} and S_{min} . Equation (2) refers to the average acceleration rate, a_{minlc} , between S_{min} and S_{lc} . The lane changing location of individual participants was determined by the position of the road exceeding 3.25 m in lane width based on LPM data from the outermost line in the acceleration lane. Equation (3) refers to the average acceleration rate, $a_{minexit}$, between S_{lc} and S_{exit} . The reason for setting two average acceleration rates as analysis indicators to explain driving behavior is to comprehend acceleration behavior from the minimum speed point to the end of the merging section or to the lane changing location. A high value for $S_{difference}$, a_{minlc} , or $a_{minexit}$ can be understood to indicate unstable driving behavior since the participant believes that the length of the acceleration lane is not sufficient to recognize the approach of a vehicle driving on the main line. Thus, using these indicators, we compared the relative driving performance of the participants in all scenarios.

$$S_{difference} = S_{entry} - S_{min} \quad (1)$$

$$a_{minlc} = \frac{(S_{lc})^2 - (S_{min})^2}{2D_{minlc}} \quad (2)$$

$$a_{minexit} = \frac{(S_{exit})^2 - (S_{min})^2}{2D_{minexit}} \quad (3)$$

where $S_{difference}$ denotes to the speed difference (km/h) between S_{entry} and S_{min} , a_{minlc} denotes to the average acceleration rate (m/s²) between S_{min} and S_{lc} , D_{minlc} denotes to the distance (m) between the point of S_{min} and the point of S_{lc} , $a_{minexit}$ denotes to the average acceleration rate (m/s²) between S_{lc} and S_{exit} , and $D_{minexit}$ refers to the distance (m) between the point of S_{min} and the point of S_{exit} .

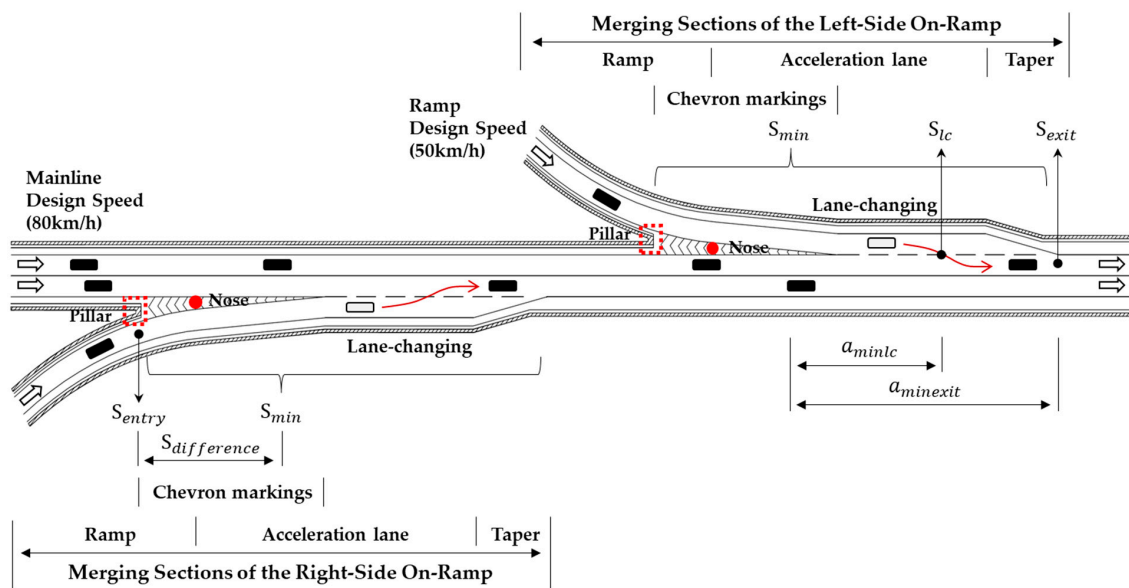


Figure 4. Analytical indicators in the on-ramp merging sections.

4. Results

4.1. Speed Behavior

This study conducted a VR driving experiment for all scenarios to analyze driving behavior according to merging direction and the length of the acceleration lane in the merging sections of the UUR junction. To analyze the driver behavior at the merging section of the UUR junction, two measures, speed and lane changing locations, were used. Figure 5 shows the average speed profile of the subjects plotted for each scenario. The graphs compare speed changes at the right-side (RS) and the left-side (LS) merging scenarios according to the same acceleration lane length. This comparison shows relatively similar speed changes regardless of acceleration lane length. However, unlike the RS scenarios, the results of LS scenarios show that the speed entering the acceleration lane decreased more for left-side merging cases. Furthermore, in LS scenarios, the longer the acceleration lanes were, the fewer the speed decreases were and the lower acceleration was thereafter.

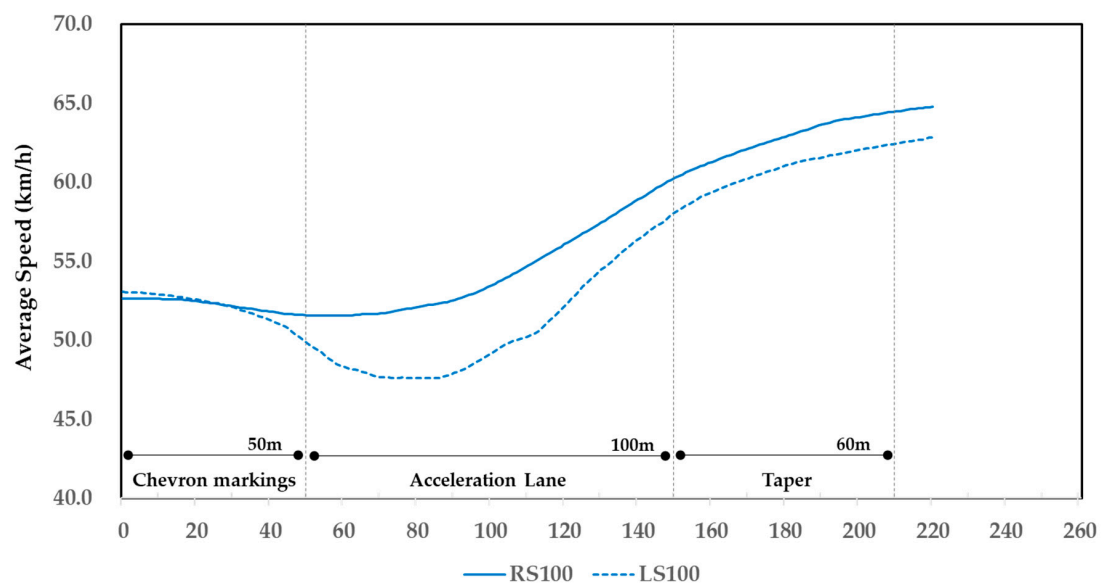


Figure 5. Cont.

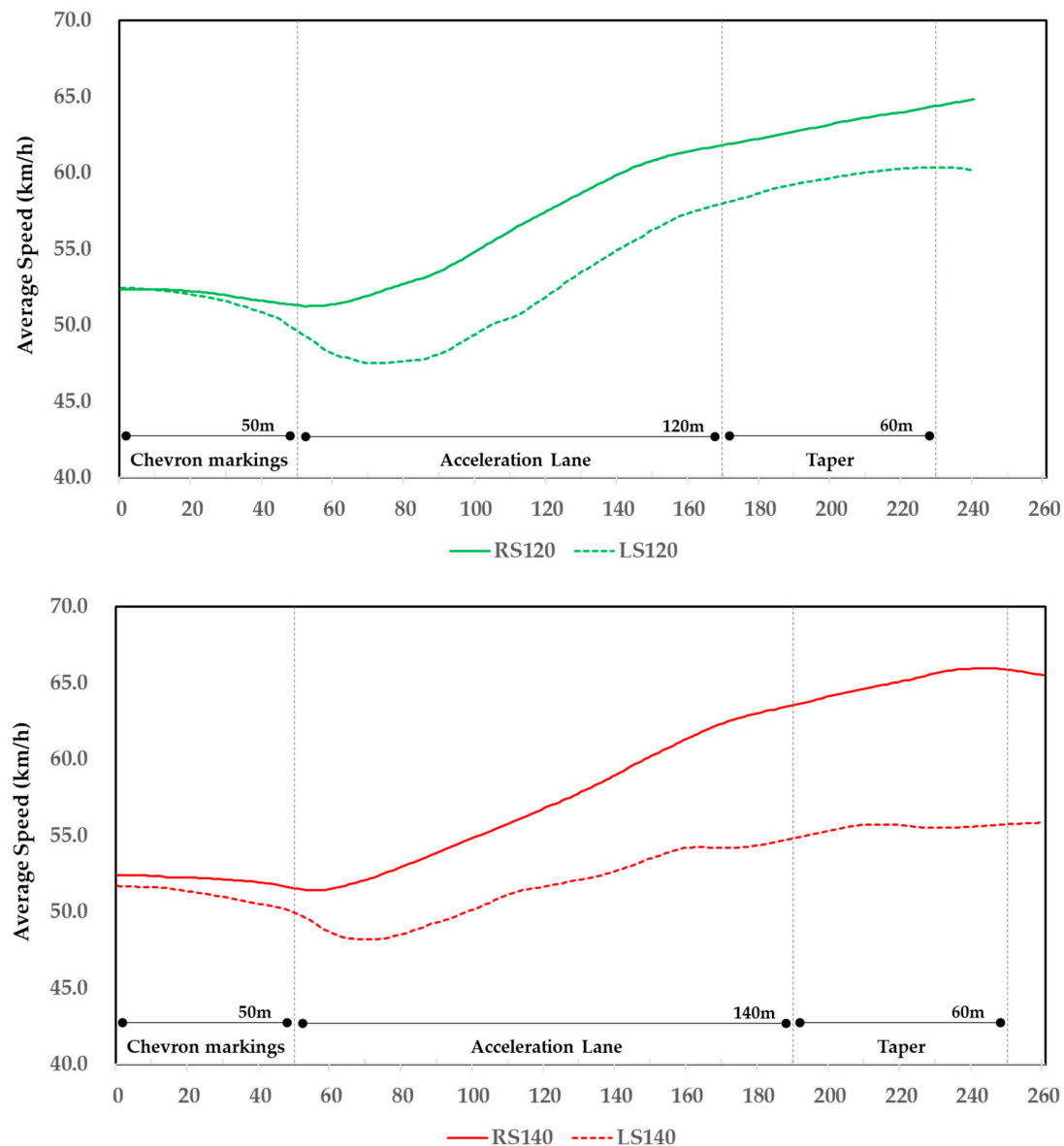


Figure 5. Average speed profiles in the scenarios.

4.2. Lane Changing Behavior

Previously, we described lane changing locations in the merging section as the position of the road where LPM exceeded the acceleration lane width, 3.25 m, based on LPM log data. All participants finished changing lanes within the acceleration lane in the merging section. There was a relatively different distribution of lane changing behavior between results for RS and LS scenarios based on acceleration lane length. Figure 6 shows the box plot for lane changing locations. According to the average lane changing locations for each scenario, the drivers in the RS100 scenario changed lanes at an average distance of 62.1 m, and the LS100 changed lanes at an average distance of 49.2 m. The drivers in the RS120 changed lanes at an average distance of 64.7 m, while the drivers in the LS120 changed lanes at an average distance of 52.2 m. In the RS140, the drivers changed lanes at an average distance of 73.7 m, while in the LS140, the drivers changed lanes at an average distance of 68.7 m. Overall, as the acceleration lane lengths increased, lane changing occurred at a later location. Further, in scenarios 100 m and 120 m for the acceleration lane lengths, the drivers in the LS scenarios changed lanes about 12.6 m to 12.9 m earlier on average than in the RS scenarios. The average lane changing location appeared earlier in LS140 than in

RS140. However, the difference was 5.0 m, which was relatively small compared to the previous two pairs of scenarios.

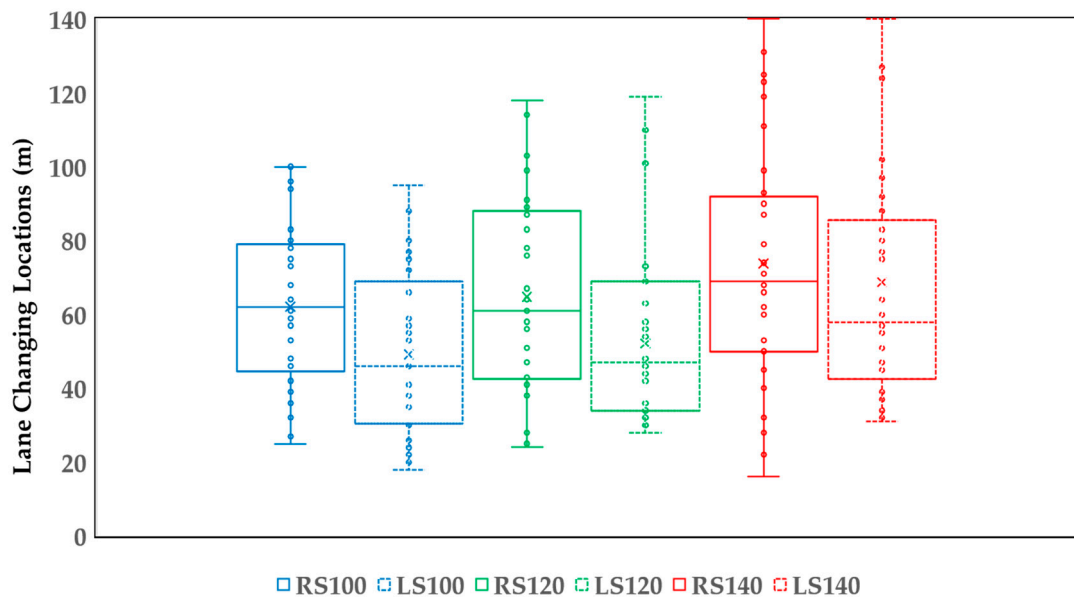


Figure 6. The box plot for lane changing locations.

4.3. Statistical Significance of Analytical Indicators

The average speed profile and distribution of lane changing locations were analyzed for each scenario as described above. Then, paired *t*-tests were conducted to confirm the statistical significance of the difference in driving behavior between the scenarios using the analytical indicators, including $S_{difference}$, a_{minlc} , $a_{minexit}$, and the lane changing locations described in Section 3.3 to explain the driving characteristics in the merging section. Moreover, statistical analysis results were investigated largely in three comparison groups as follows: (1) comparison of results from RS and LS scenarios for the same acceleration lane length, (2) comparison according to the acceleration lane length for RS scenarios, and (3) comparison according to the acceleration lane length for LS scenarios.

Firstly, Table 1 shows the paired *t*-test results for the speed difference, $S_{difference}$. As shown in the results of the RS and LS comparison with the same length of acceleration lane, the means and standard deviations of the speed difference for LS scenarios were bigger than those for RS scenarios. Based on the mean difference, it was statistically significant at 6.00 km/h ($p = 0.001$) for results comparing RS100 and LS100, 4.83 km/h ($p = 0.001$) for results comparing RS120 and LS120, and 2.37 km/h ($p = 0.001$) for results comparing RS140 and LS140. Meanwhile, no statistical significance was found in the results of the comparison by length of the acceleration lane for RS merging ($p = 0.316$, $p = 0.502$). However, the results of comparison by length of the acceleration lane for LS merging had statistical significance ($p = 0.004$, $p = 0.013$). Therefore, it was found that the $S_{difference}$ of RS and LS scenarios was different in the even same geometric conditions. For LS scenarios, the longer the acceleration lane, the smaller the mean, and the standard deviation of $S_{difference}$ was observed.

Secondly, Table 2 shows the paired *t*-test results for the first acceleration rate, a_{minlc} . This acceleration rate for LS100 was statistically higher by 0.26 m/s² ($p = 0.004$) than that for RS100. However, in the comparisons with 120 m and 140 m length of acceleration lanes, there were no statistically significant differences ($p = 0.557$, $p = 0.772$). The mean differences for comparisons 100 m and 120 m, and 120 m and 140 m lengths of acceleration lanes of RS scenarios were not statistically significant ($p = 0.443$, $p = 0.151$), while for LS scenarios, the acceleration rate as the length of the acceleration lane increased with statistical significance ($p < 0.001$, $p = 0.032$).

Table 1. The paired t -test results for $S_{difference}$.

Comparison Group	Scenarios	Mean (km/h)	S.D. (km/h)	Paired Differences		
				Mean	t	p-Value
Right side and left side	RS100	3.73	4.09	−6.00	−3.99	0.000 *
	LS100	9.73	9.18			
	RS120	2.83	3.22	−4.83	−3.65	0.001 *
	LS120	7.66	6.54			
	RS140	2.33	2.70	−2.37	−3.52	0.001 *
	LS140	4.71	3.18			
Length of acceleration lane	RS100	3.73	4.09	0.90	1.02	0.316
	RS120	2.83	3.22			
	RS120	2.83	3.22	0.50	0.68	0.502
	RS140	2.33	2.70			
	LS100	9.73	9.18	2.07	3.09	0.004 *
	LS120	7.66	6.54			
	LS120	7.66	6.54	2.95	2.64	0.013 *
	LS140	4.71	3.18			

* The mean difference is significant at the 0.05 level.

Table 2. The paired t -test results for a_{minlc} .

Comparison Group	Scenarios	Mean (m/s ²)	S.D. (m/s ²)	Paired Differences		
				Mean	t	p-Value
Right side and left side	RS100	0.42	0.26	−0.26	−3.05	0.004 *
	LS100	0.68	0.43			
	RS120	0.46	0.24	−0.04	−0.56	0.577
	LS120	0.50	0.30			
	RS140	0.39	0.21	0.02	0.29	0.772
	LS140	0.37	0.22			
Length of acceleration lane	RS100	0.42	0.26	−0.04	−0.78	0.443
	RS120	0.46	0.24			
	RS120	0.46	0.24	0.07	1.47	0.151
	RS140	0.39	0.21			
	LS100	0.68	0.43	0.18	3.85	0.000 *
	LS120	0.50	0.30			
	LS120	0.50	0.30	0.13	2.23	0.032 *
	LS140	0.37	0.22			

* The mean difference is significant at the 0.05 level.

Thirdly, Table 3 shows the paired t -test results for the second acceleration rate, $a_{minexit}$. This acceleration rate for LS 100 was statistically higher by 0.12 m/s² ($p = 0.032$) than that for RS100. However, in the comparisons with 120 lengths of acceleration lanes, there were no statistically significant differences ($p = 0.626$). The acceleration rate for LS140 was statistically lower by 0.15 m/s² ($p < 0.001$) than that for RS100. The mean differences for comparisons 100 m and 120 m, and 120 m and 140 m lengths of acceleration lanes of LS scenarios were statistically significant ($p < 0.001$, $p < 0.001$).

Table 3. The paired *t*-test results for $a_{minexit}$.

Comparison Group	Scenarios	Mean (m/s ²)	S.D. (m/s ²)	Paired Differences		
				Mean	t	p-Value
Right side and left side	RS100	0.45	0.18	−0.12	−2.24	0.032 *
	LS100	0.57	0.32			
	RS120	0.38	0.14	−0.02	−0.49	0.626
	LS120	0.40	0.19			
	RS140	0.37	0.20	0.15	4.26	0.000 *
	LS140	0.21	0.07			
Length of acceleration lane	RS100	0.45	0.18	0.08	2.07	0.046 *
	RS120	0.38	0.14			
	RS120	0.38	0.14	0.01	0.30	0.765
	RS140	0.37	0.20			
	LS100	0.57	0.32	0.18	5.68	0.000 *
	LS120	0.40	0.19			
	LS120	0.40	0.19	0.18	5.26	0.000 *
	LS140	0.21	0.07			

* The mean difference is significant at the 0.05 level.

Finally, Table 4 shows the paired *t*-test results for lane changing locations. According to the box plot of lane change points in Figure 6, in the LS scenarios for 100 m and 120 m lengths of acceleration lanes, subjects changed lanes about 12.9 m to 12.6 m earlier than in the RS scenarios, with statistical significance ($p = 0.018$, $p = 0.024$). Participants in the LS140 changed lanes about 5.0 m earlier than in the RS140. However, there was no statistical significance ($p = 0.529$). Also, it was not statistically significant for RS scenarios ($p = 0.542$, $p = 0.204$), but the lane changing location for LS140 was statistically 16.6 m higher than for RS140 ($p = 0.012$).

Table 4. The paired *t*-test results for lane changing locations.

Comparison Group	Scenarios	Mean (m)	S.D. (m)	Paired Differences		
				Mean	t	p-Value
Right side and left side	RS100	62.09	21.35	12.9	2.50	0.018 *
	LS100	49.23	22.69			
	RS120	64.74	26.81	12.6	2.36	0.024 *
	LS120	52.17	22.91			
	RS140	73.74	33.06	5.00	0.64	0.529
	LS140	68.74	31.88			
Length of acceleration lane	RS100	62.09	21.35	−2.7	−0.62	0.542
	RS120	64.74	26.81			
	RS120	64.74	26.81	−9.0	−1.30	0.204
	RS140	73.74	33.06			
	LS100	49.23	22.69	−2.9	−0.64	0.529
	LS120	52.17	22.91			
	LS120	52.17	22.91	−16.6	−2.67	0.012 *
	LS140	68.74	31.88			

* The mean difference is significant at the 0.05 level.

5. Discussion

In this study, statistical differences in driving behavior were investigated using scenarios using log data such as speed and LPM extracted from a VR driving experiment. As a result, it was found that if the acceleration lane is extended at intervals of 20 m from the standard acceleration lane length, the $S_{difference}$, a_{minlc} , and $a_{minexit}$ of the ramp vehicle tend to become smaller. Although the driving behavior was not significantly changed in RS scenarios, which are relatively familiar road environments for many drivers, changes in LS scenarios were noticeable. Thus, in the case of the merging section on the left-side on-ramp, there is a need for a larger extra distance than the minimum acceleration lane length for the driver to recognize the traffic environment, change lanes, and enter the main line.

The phenomenon of reduced speed at the merging sections we discussed earlier is associated with the driving behavior of checking visually for vehicles driving on the main line. This can also be explained by the gaze ratio based on visual fixation counts obtained from a pair of Tobii Pro Glasses 3 [30], which are a device capable of extracting data on visual behavior worn by the participants in the VR driving experiment. As lane changes are required on the road, all gaze zones visible to the driver's eyes were divided into areas of interest, such as the front window, side mirrors, and inside of the vehicle [31]. A short merging section was divided into approximately 20 m intervals. The change in gaze ratio in the side mirror by direction was analyzed for each section in more detail. Figure 7 shows the average gaze ratio of the right- and left-side mirrors among the visual fixation count data in all front areas. The visual fixation ratio for the right-side mirror in the C and D sections of the acceleration lane was approximately 25% to 40% for LS scenarios. This was relatively higher than the visual fixation ratio for the left-side mirror. In this regard, it is believed that the phenomenon of more decrease in speed in LS scenarios is due to drivers having to turn their heads more to look at the right-side mirror to recognize vehicles driving on the main line. During this short process, the driver naturally slows down while looking longer into the right-side mirror.

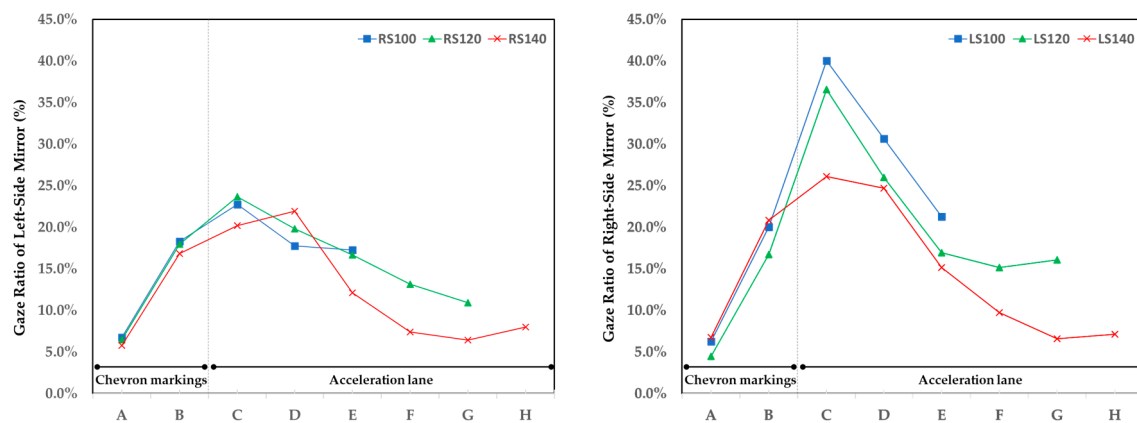


Figure 7. Average gaze ratio of left- and right-side mirrors.

To compare the acceleration behavior of RS and LS scenarios, we analyzed the two average acceleration rates as analytical indicators. Figure 8 shows the scatter plot of the three analytical indicators, $S_{difference}$ and a_{minlc} , or $S_{difference}$ and $a_{minexit}$. In the RS scenarios, in contrast to the LS scenarios, there was a relatively larger number of subjects with an $S_{difference}$ of 0, that is, subjects accelerating without decreasing their speed while entering the acceleration lane. The LS scenarios, such as LS100 and LS120, were found to have a relatively high $S_{difference}$ and high average acceleration rates. The scatter plot appears long and slanted to the upper right. According to the simple linear regression model for $S_{difference}$ and $a_{minexit}$ of LS scenarios, the values of R^2 were 0.7988 for LS100 and 0.8598 for LS120, which were relatively high compared to RS scenarios. There was, however, a less consistent tendency in the value of a_{minlc} than in the value of $a_{minexit}$. This indicates

that driver acceleration behavior when changing lanes varies. LS140 is comparable to RS scenarios in terms of $S_{difference}$ and shows relatively stable trends and values of less than 1.0 m/s^2 in terms of average acceleration.

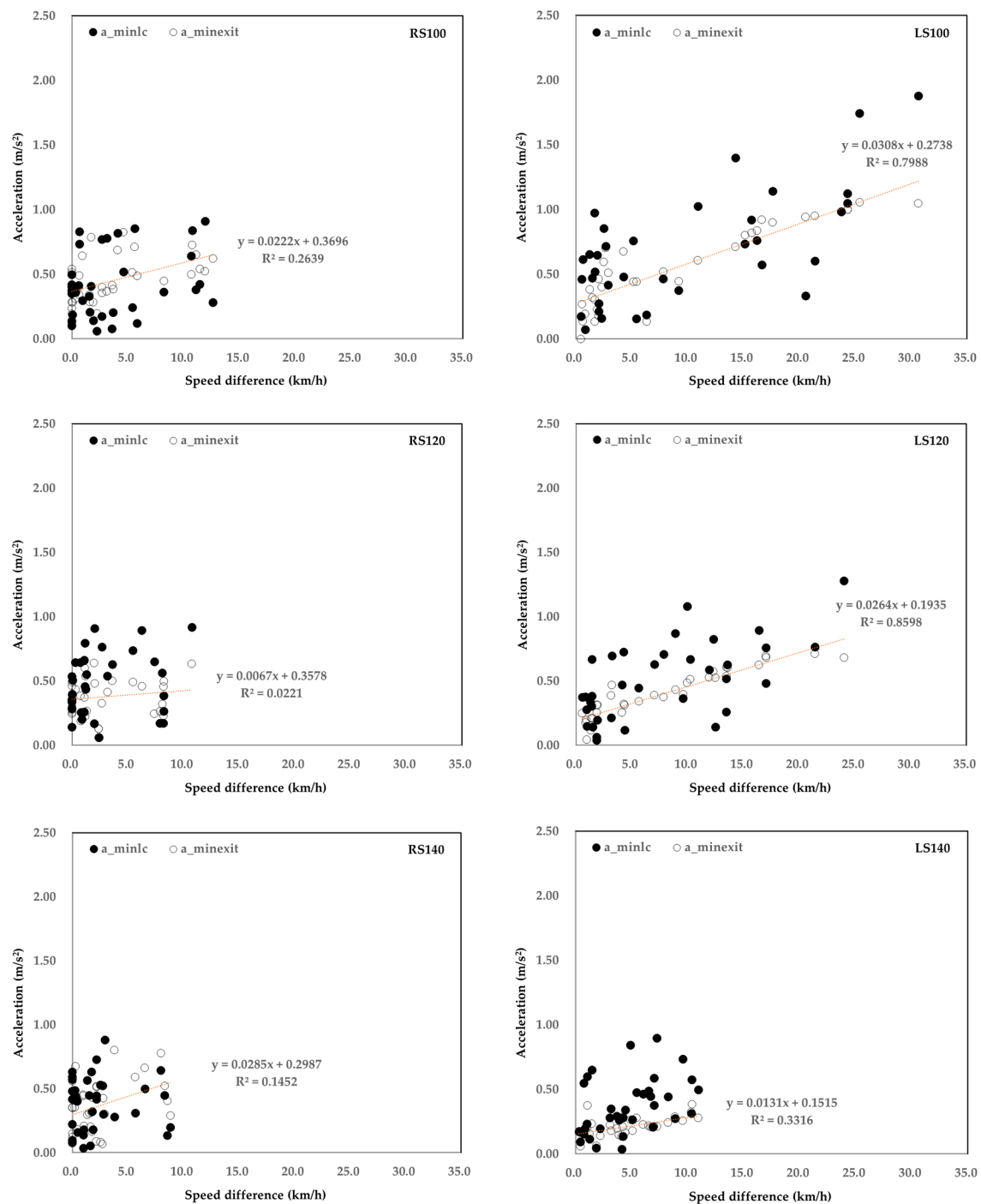


Figure 8. The scatter plot for the analytical indicators.

Based on the results of the previous analysis, there was a difference in driving behavior in the merging sections depending on the direction of the ramp. In addition, there was more stability in driving behavior depending on the acceleration lane length. Consequently, according to the findings of this study, when designing the merging section of the left-side on-ramp, the extra distance is recommended rather than the current minimum acceleration lane length. It is proposed that the extra distance be increased by 1.4 times what is currently

required. This can be understood as a margin of approximately 2 s or more when driving in the acceleration lane. This design direction may assist in alleviating sudden acceleration or deceleration behavior that may occur at the merging sections in the UUR junction.

6. Conclusions

Demand for UURs has increased steadily in recent years around the world to reduce traffic congestion in urban areas. It is important to introduce network-type underground roads in UUSs to make efficient underground roads. In this study, VR driving experiments were conducted to compare driving behavior in terms of the direction of the ramp and the length of the acceleration lane in the merging sections of the UUR junction based on double-decker tunnels. As a result, it was found that driving behavior was different between the right-side and left-side merging sections. Particularly, the vehicle's speed on ramps conspicuously decreased in the left-side merging sections. Driving behavior became more stable as the length of the acceleration lane increased. Furthermore, it was also found that acceleration behavior was statistically lower in left-side merging sections when the acceleration lane had additional distance.

Therefore, from this perspective, to ensure the safe design of left-side merging sections, a separate acceleration lane length standard is required, in addition to an extra distance longer than the existing standard. However, if the acceleration lane is extended, the large-section tunnel will become longer, resulting in increased construction costs. As such, experts must evaluate it in terms of its technical and economic feasibility. Finally, due to the increasing interest in UURs, much research into related design factors is necessary to ensure users' safety on underground roads. In the future, we hope that the optimal design technology for UURs will reflect various driver behavior studies.

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