Effect of Road Geometry on Free-Flow Speed: An Empirical Analysis using ETC 2.0 Data

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Understanding free-flow speed and its variance is important to evaluate the safety and performance of expressways. Not only the geometric factors considering directly in geometric element design criteria, but also other factors which are not explicitly considered (for ex., number of lanes, width of lanes, center median etc.) affect the variation of free-flow speed. Previous studies have less focused on expressways and mainly utilized spot speed data. In this study, we explore the combined effect of road geometry on driver's free-flow speed selection. Both direct and indirect geometric factors are considered. Probe speed data recorded from ETC 2.0 systems of general vehicles travelled on Tomei Expressway are used. In addition, detector data, incident data and rainfall data were also utilized to eliminate congestion and weather effect on free-flow conditions. Output of this study may be useful to impose safety regulations, design consistency evaluations and as an input for travel time estimators.

Key Words : *Free-Flow Speed, Road Geometry, Expressways, ETC 2.0,*

1. INTRODUCTION

Ensuring a safe and efficient road environment is important for the smooth functioning of a highway system. Thus, studying the drivers' speeding behavior on different road geometries under free-flow conditions would provide valuable input for road safety evaluation[1)]. In addition to safety evaluations, the free-flow speed is used for many other traffic applications such as setting of speed limits[1)],design consistency evaluation[2)] and travel time estimation purposes[3)].

It has been proven in the literature that applying the design speed concept is insufficient to reduce the speed variations[4)]. That is because the highway elements are explicitly designed and some road elements (i.e., lane width, no of lanes), which are not directly related to design speed, may still have significant impacts on free-flow speed[4)]. Therefore, it is important to consider all of such elements and study how the complete information on geometrical features affects drivers' free-flow speed selection.

Many researchers have conducted studies on free-flow speed for different road classifications and concluded that various geometric elements affect free-flow speed[2,5–7)]. For instance, Fitzpatrick et al[8)] studied the factors affecting driver speed on horizontal curve sections in suburban streets. Their results explained that posted speed limit, deflection angle and access density have significant impact on driver's free-flow speed in horizontal curve sections on suburban streets. Nie et al[9] studied the driver speed behavior of horizontal curves on freeways and concluded that the driver's speed is controlled more by traffic condition and speed limits than by the geometric elements in freeways. However, their study has not considered the effect of vertical alignment inside the horizontal curve sections of freeways.

Most previous studies on free-flow speed have conducted utilizing speed data collected in the field using measuring devices such as radar guns[8,10,11]. In such studies the study sites have to be pre-determined. As a result, the number of observations and the number of sites available for the analysis are also limited[4]. Moreover, the recorded data contains human and bias errors in addition to the instrumental errors. Some recent studies have captured data using GPS loggers mounted in test vehicles[2,5] aiming to eliminate such limitations. However, there is a possibility that those data contains some biasness because the driver in the experiment already knows that the purpose of the trip is a field test. Thus, it is clear that previous studies have not adequately addressed the influence of road geometric characteristics on drivers' free-flow speed selection, particularly on expressways. Considering these, in this study we explore the combined effect (both direct and indirect geometric factors) of road geometry on driver's free-flow speed selection. In contrast with the previous studies, this analyse consideres the combined effect of both horizontal and vertical alignments on free-flow speed on expressway sections.

The advantage of using ETC 2.0 data, which we use in this study, is that all the previously mentioned limitations can be eliminated. However, it is required to remove the effect of outside factors other than road geometry on free-flow speed. For example, weather is a significant factor on free-flow speed[12] and hence speed data recorded especially during rainfall and snowfall need to be eliminated from further analysis. Though removing such effects in a field survey is quite straightforward, identifying them using data records and eliminate the effect from speed database is quite challenging.

This paper is structured as follows: The next section will discuss the details of all data sources we used. Then, steps followed in data preparation are described. This is followed by the analysis. Finally,

Fig. 1 Plan view of Tomei Expressway

conclusions and recommendations for further studies are presented.

2. DATA

The Tomei Expressway(**Fig.1**), which connects Tokyo and Nagoya, was selected for the analysis and speed data of the vehicles were extracted using ETC 2.0 database. In addition to ETC 2.0 database, loop detector data, precipitation data, incident data were also utilized to extract vehicles which traversed at free-flow speed. Moreover, road geometric data was used to quantify the road alignment. Details of these data sources are described in following sub-sections.

2.1 ETC 2.0 data

These are the data recorded by the ETC 2.0 vehicle on-board systems in the vehicles travelled on Tomei Expressway. This on-board car navigation system records the GPS position, GPS time and the speed of vehicle and stored temporary until the vehicle meets an ITS spot to upload the record. Subsequently, the on-board system is reset and starts recording data from the next point as a new record until the vehicle arrives in the next ITS spot. A schematic diagram for such system is shown in **Fig. 2**. The data is recorded in 100m or 200m intervals based on the commercial type of the on-board system[13]. The organized database provides the data received time, decoded vehi-

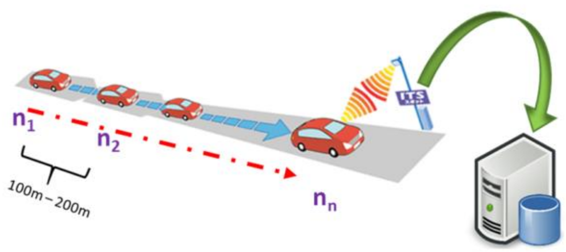


Fig. 2 ETC 2.0 data recording system

ﾃﾞｰﾀ受信時刻	車両情報	GPS期日時刻	経度	緯度	高度	速度	KP	路線ｺｰﾄﾞ	上下
20140209235822_	001302000000	2.01402E+13	138.9007	35.1839	0	97	97.723	1010	3
20140209235822_	001302000000	2.01402E+13	138.9001	35.1822	0	98	97.925	1010	3
20140209235822_	001302000000	2.01402E+13	138.8996	35.1804	0	104	98.133	1010	3
20140209235822_	001302000000	2.01402E+13	138.8993	35.1785	0	104	98.341	1010	3
20140209235822_	001302000000	2.01402E+13	138.899	35.1767	0	102	98.546	1010	3
20140209235822_	001302000000	2.01402E+13	138.8986	35.1749	0	101	98.75	1010	3
20140209235822_	001302000000	2.01402E+13	138.8978	35.173	0	96	98.967	1010	3
20140209235822_	001302000000	2.01402E+13	138.8968	35.1714	0	97	99.168	1010	3
20140209235822_	001302000000	2.01402E+13	138.8955	35.1699	0	95	99.376	1010	3
20140209235822_	001302000000	2.01402E+13	138.8936	35.1682	0	86	99.633	1010	3
20140209235822_	001302000000	2.01402E+13	138.892	35.1669	0	93	99.84	1010	3

Fig. 3 Sample data from ETC 2.0 Database

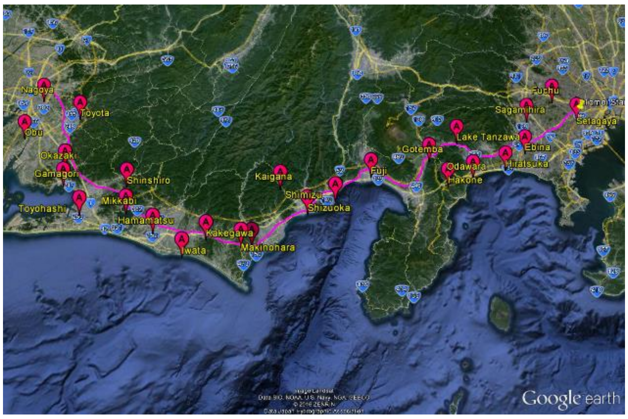


Fig. 4 Locations of weather stations

cle ID, route code, route direction and corresponding kilometer point of the recorded GPS position on the road in addition to the data recorded by the vehicle. Sample of ETC 2.0 database is shown in **Fig. 3**. Data recorded between 0km – 346 km of Tomei Expressway from 2013 January to 2014 September is provided by Central Nippon Expressway Company (NEXCO) for this analysis.

2.2 Traffic Data

These are the data recorded from induction loop detectors fixed in Tomei Expressway. Data is recorded around the clock and provide traffic volume, flow, speed and occupancy aggregated in 5 minute intervals. In addition, the data also contains the location of each detector and the section of the road which the recorded parameters of the detector can be utilized to estimate travel time.

2.3 Incident Data

The information of non-recurrence events occurred along Tomei Expressway from 2013 January to 2014 September has been obtained for the analysis. One entry contains the date, starting time, ending time, start of location, end of location, type of incident, route number and direction of the road. Incidents, such as accidents, vehicle breakdowns , construction sites, imposing temporary speed regulations, congestion and road obstacles were captured in these data.

2.4 Precipitation Data

Rainfall and snowfall data from 26 weather stations(**Fig. 4**) located closely to the alignment of Tomei Expressway were obtained from Japan Metrological Agency. The daily aggregated rainfall and snowfall in millimetres are available for the same duration of traffic data described in previous sections (i.e., from 2013 January to 2014 September).

2.5 Geometric Data

The geometric dataset contains the starting and ending points of sections, section type(horizontal curve,vertical curve, clothoid etc.) and the paratemeter values of both horizontal and vertical alignment (i.e., curvature and gradient) along the Tomei Expressway.

Considering the availability of all types of data, ETC 2.0 data between 0km – 268.9km of Tomei Expressway recorded during 2013 January, 2013 April to November and 2014 June to September were selected for the analysis.

3. DATA PREPERATION

The speed data recorded in all traffic states are mixed in one database and the data contains the recording errors as well. Therefore, the following data cleansing and data reduction steps were considered to eliminate data errors and extract the speed data recorded during free-flow traffic state.

3.1 Data Cleansing

a.) Removal of server error

In some recording cycles of one vehicle, all the recorded speed data has the value of either 0 km/hr or 255 km/hr which is due to an error of the system [13]. Therefore, the speed data contains these values were removed from the data set.

b.) Removal of data recording error

In addition to the recorded speed, the vehicle's speed at each location was calculated using the GPS coordinates and GPS time and compared with the recorded spot speed. If the difference between these two speed values are greater than 20 km/hr, the recorded data point was removed from ETC 2.0 dataset as this is a result of GPS errors during data recording[13].

c.) Removal of points with unrealistic acceleration

Based on the data reported by Mehar et al.,[14] we consider that the maximum acceleration for a passenger car is 2 m/s^2. Akcelic et al.[15] reported that the maximum deceleration of a passenger car is approximately -2 m/s^2. Obvioulsy these values might not be the exact values for expressways. However, these values provide reasonable and conservative values for our purpose. Hence, 2 m/s^2 and -2m/s^2 were considered as the maximum acceleration and deceleration values respectively for a passenger car on a expressway. Accordingly, if the acceleration/deceleration profile of a vehicle contains values beyond the range of -2m/s^2 to 2m/s^2 , it might be due to data recording errors or a special incident such as a head to head collision. Both of these effects need to be removed and therefore, the acceleration profile of each vehicle was generated using the data in ETC 2.0 database and the data points with acceleration/deceleration beyond the range of -2m/s^2 to 2m/s^2 were eliminated from the dataset. **Fig. 5** shows an example for such case. The speed profile of the vehicle seems to be acceptable but when we observe the acceleration profile, it can be seen that some of the acceleration values are quite unacceptable.

3.2 Data Reduction

a.) Eliminate Congestion

The analysis requires to extract the speed data from the cleansed speed database which are recorded during free-flow traffic state. The Highway Capacity Manual defined free-flow state as the condition when the flow rate is less than 1000 pc/h/ln[16]. Hence, the free flow rate for 2 lane and 3 lane sections were considered as 2000 pc/h & 3000 pc/h respectively. Then, the traffic detectors located in the basic segments of Tomei Expressway downbound direction were selected and the flow-density diagram for each detector was generated using one-month traffic detector data as shown in **Fig. 6**. The free flow density value for each detector was estimated graphically and based on the mode value of all detectors, 24 veh/km and 35 veh/km were selected as free flow density value for 2 lane and 3 lane sections respectively. If both traffic flow and density at a given time is less than the estimated free-flow rate and density, that time is identified as a time of free-flow state. Accordingly, the flow rate and density value recorded at 5 minutes interals in traffic database were compared with the free-flow traffic parameters(flow rae and density) to identify free-flow time periods. Then, the speed data recocrded in those time periods were extracted for further analysis.

b.) Remove the effect from non-recurrence events

Non-recurrence events such as accidents and road maintenance works would draw the attention of drivers and also could create traffic bottlenecks. As a result, the driver's free-flow speed might be affected. To eliminate this effect, the date, time and affected road section by the non-recurrence events were identified from incident database and speed data recorded during those times were removed accordingly.

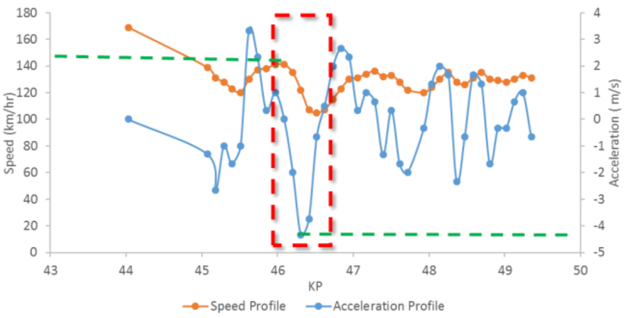


Fig. 5 Comparison of speed profile and acceleration profile of one vehicle

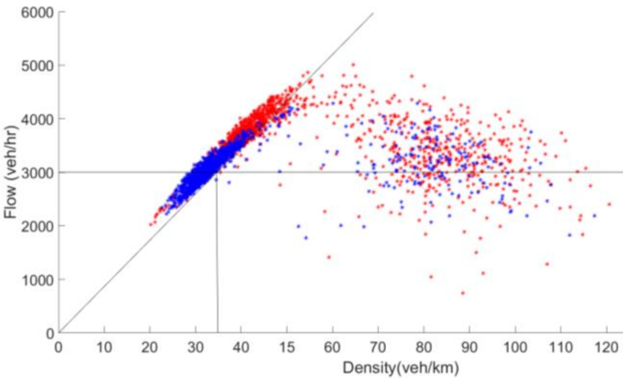


Fig. 6 Fundamental Diagram of one detector using one month traffic data and estimation of free-flow density

c.) Eliminate weather effect

The effect of weather, especially the precipitation, on speed has been proved by many researchers in the literature[12]. Therefore, to remove this effect, the nearest weather station to the recorded speed data point was selected and if the weather station has no recorded precipitation during the data recorded day, the point is considered for the analysis or otherwise it was removed from the analysis.

After removing all these errors and external effects that may affect free-flow speed, a data set that contains free-flow speed data was obtained for analysis. Details of the data analysis are presented in the next section.

4. ANALYSIS

The Tomei Expressway downbound direction has 209 horizontal curve sections. Since the objective of this research is to study the effect of road geometry on free-flow speed, only the horizontal curves located in basic segments of the expressway have been selected for this analysis. Because, presence of a ramp, tunnel, interchange or a parking area can change the driver's free-flow speed. For example, drivers may reduce the speed to stop in the parking area. Removing such sections, 110 horizontal curve sections with a radius varying between 550m -10,000m have been identified. All the speed data belongs to each section was extracted from the free-flow speed database. Before calculating the average free-flow speed of each section, boxplot for each individual section was drawn and removed the speed data beyond the upper and lower limits to remove further anomalies.

The relationship between average free-flow speed of horizontal curve sections vs horizontal curvature is shown in **Fig. 7** and even though the graph shows a decreasing of free-flow speed when the curvature increases, no statistically significant relationship has been found from linear regression. Also, the free-flow speed data is highly scattered and a range of free-flow speed can be seen for one curvature value in **Fig. 7.** Hong et al. [17] speculate that the effect of the vertical alignment inside the horizontal curve section could be the reason for observing different free-flow speed values for sections with same horizontal curvature. **Fig. 8** shows the variation of free-flow speed with the variation of horizontal curvature and vertical grade value at the start of the horizontal curve section. This figure clearly explains that the free-flow speed between two sections with same horizontal curvature value can be different according to its vertical grade value. Specifically, the free-flow speed values of the horizontal curve sections located in a downgrades are higher than the sections located in upgrades and in some cases, the free-flow speed value has already exceeded the statutory speed limit which is 100 km/hr.

Fig. 9 shows the standard deviation of the free-flow speed of horizontal curve sections with the variation of curvature and vertical grade value at the start of the horizontal curve sections. The figure shows higher variation of free-flow speed in low curvature sections compared to higher curvature sections. One possible cause for this observation is that some drivers try to maintain higher speeds in low curvature sections which are almost like straight sections. However in higher curvature sections, the high speed drivers try to maintain the average driver's speed because of the effect of horizontal curvature. Note that a limited number of data points were available to generate **Fig. 8** and **Fig. 9** (110 horizontal curve sections). However, the combined effect of verticle and horizontal geometries on drivers' free-flow speed selection can be clearly visualized through these figures.

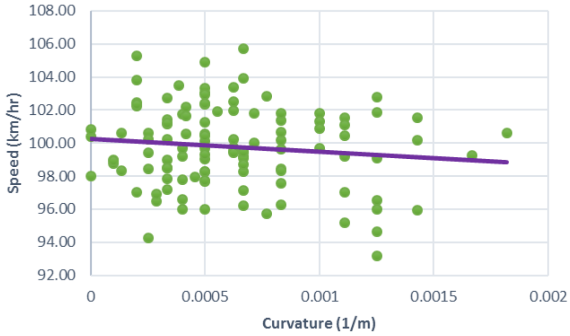


Fig. 7 Relationship between average free-flow speed of horizontal sections and curvature

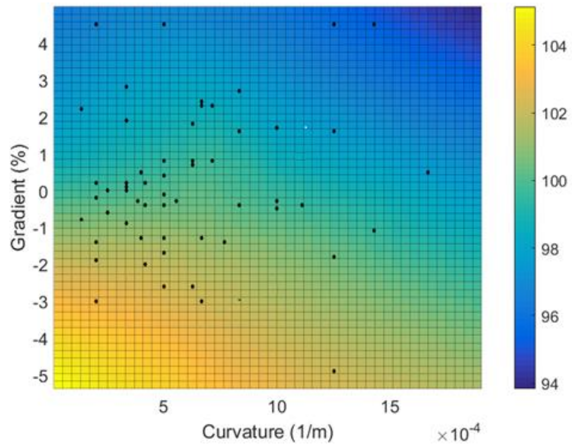


Fig. 8 free-flow speed variation with curvature and vertical grade value

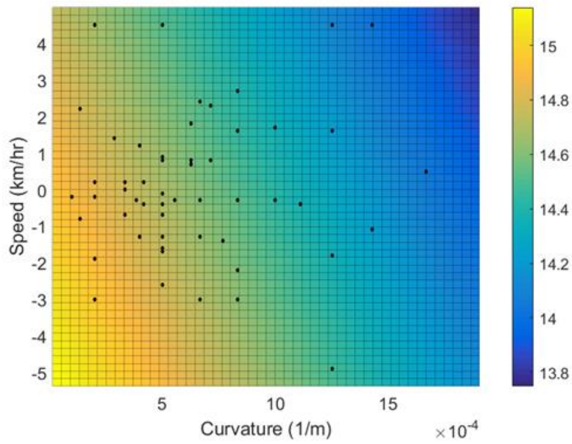


Fig. 9 variation of standard deviation of free-flow speed of sections with curvature and vertical grade value

In order to further quantify the effect of road geometry on free-flow speed, information, such as radius, length of the previous transition section, length of the following transition section, gradient value at start of the section, gradient value at the end of the section, length of the section, deflection angle and speed limit for each horizontal section was extracted using the geometric database. The radius was transformed to the square root of the radius to consider the linear relationship between the speed and the square root of the radius when a particle moving in a circular path. Then, multiple linear regression was performed for the 110 horizontal curve sections considering the geometric parameters mentioned above as exogenous variables and the free-flow speed as endogenous variable. The result showed that only the speed limit and the gradient value at the start of the horizontal curve are statistically significant at 95% confidence level (R^2 =0.35). Previous studies have also concluded that speed limit significantly affects the free-flow speed[18)] and this is due to the reason that most of the drivers follow the speed limit value to avoid getting confessed. Observing vertical grade value at the start of the horizontal curve as a significant variable evident that free-flow speed of an expressway is affected by the vertical alignment of the road section.

The vertical alignment inside the horizontal curves were further observed and found that these sections can be further categorized based on the vertical alignment. The horizontal curve sections located in an upgrade or downgrade vertical alignment was considered as category 1 and the sections which contains a part of a vertical curve in the vertical alignment was considered as category 2. All the other sections, which contains a full vertical curve inside the vertical alignment was considered as category 3(**Table 1**).

Prior to perform multiple linear regression for each category, the following changes were made for the exogenous variables in each category.

Category 1: the vertical grade value is a constant from the start point to the end point of the horizontal curve section. Therefore, the vertigal grade of the section was considered as an exogenous variable rather than considering both vertical grade at start and vertical grade at the end because both have same value in this category.

Category 2: higher linear correlation was observed between vertical grade value at the start and end variables and therefore, only the vertical grade at the start of the horizontal curve was selected for the analysis. Besides, k-value(**Fig.10**)of the vertical curve was also considered as an additional variable.

Category 3: k-value(**Fig.10**) of the vertical curve was considered as another exogenous variable.

Outcomes of the multiple linear regression for each category are summarized in **Table 2.**

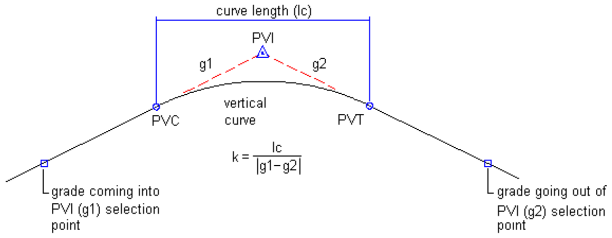
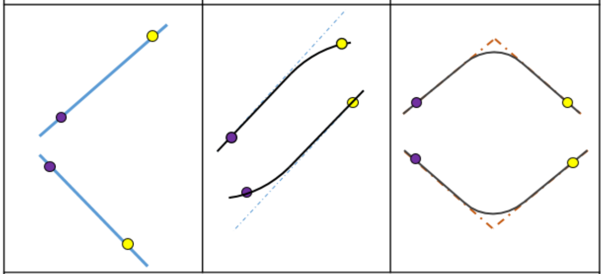


Fig. 10 k-value of a vertical curve
Source: www.autodesk.com

Table 1 shape of vertical profile inside the horizontal curve section in each considered category.

Category 1	Category 2	Category 3



Start of the horizontal curve section
End of the horizontal curve section

Table 2 Summery of Regression Analysis

Type of Horizontal Curve Sections	Significant Variables	Coefficient	p -Value	R^2
All	Speed Limit	0.0646	0.0337	0.35
	Gradient Value at Start	-0.6977	0.0000	
Category 1	Length of Previous Tangent	-7.4552	0.0158	0.72
	Length of Next Tangent	17.4754	0.0415	
	Vertical Grade	-2.8401	0.0199	
Category 2	Speed Limit	0.1132	0.0056	0.70
	Gradient Value at Start	-0.5842	0.0000	
	K-Value	-7.5899	0.0002	
Category 3	-			0.38

The results of the category 1 shows that the length of previous tangent, length of the following tangent and the vertical grade value significantly affect on free-flow speed while the speed limit, vertical grade value at the start of the section and k-value are significantly affect on free-flow speed in category 2. However, all the considered variables in category 3 were found as statistically insignificant for free-flow speed.

In this analysis, horizontal radius was not observed as a significant factor for free-flow speed selection. This explains that the free-flow speed of expressways are not affected by the presense of a horizontal curve. Probably the reason for not having any effect from the horizontal alignment might be due to the reason that horizontal radius values in expressways are higher than in other roads. The lowest radius value of the considered sections in this analysis is 550m. According to the “reversely calculated speed concept” introduced by Hong et al.[17)], the physically accommodated speed value for a 550m curve is 100 km/hr and the larger the curve radius, the larger the physically accmodated speed. Therefore, the effect of horizontal curves, which are greater than 550m, on average free-flow speed could be very low.

5. CONCLUSION

This study analyzed 110 horizontal curve sections located on basic segments of Tomei Expresway downbound direction and the range of the horizontal radius of the considered sections varies between 0m – 10,000m. Mean free-flow speed was calculated for each section using ETC 2.0 data. No significant relationship was observed between mean free-flow speeds and the curvature of horizontal curve sections. Moreover, the multiple linear regression results for all the considered cases do not recognize the radius of the horizontal section as a significant factor for the free-flow speed on considered expressway. One previous study on expressways has concluded that the free-flow speed behavior of an expressway is more controlled by the speed limit and the traffic condition. However, this study has found that the variables represent vertical alignment of the sections significantly affect on free-flow speed except in category 3. Hence, it can be concluded that the free-flow speed is affected by the vertical alignment of the road section.

Even though the horizontal alignment does not have a significant effect on an average driver (i.e., average free-flow speed), it might have an effect on high speed drivers. Moreover, the achieved speed in upstream sections might also have an effect on the driver’s speed selection on downstream sections. Therefore in future works, speed profiles of individual vehicles should be analysed to clearly understand how the geometric features affects on behaviors of individual drivers who are approaching the curve section at different speed levels.

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