Speed Mechanism in the urban residential areas with the presence of speed hump

（生活道路に設置されたハンプにおける自動車の速度メカニズムに関する研究）

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September 2019

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A dissertation submitted to the Saitama University in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by

Professor Hisashi Kubota

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Mursheda Rahman
06 June, 2019
Saitama, Japan

Dedicated to my Family

Abstract

The primary and main function of a residential street is to provide spaces where the inhabitants' can perform a variety of social activities and to provide a direct access to the adjacent buildings or facilities for pedestrian and bicyclists. Therefore, residential streets should be well designed so that the local residents can live and work there now as well as in future also. However, residential streets are now becoming unsafe for the community people because of excessive vehicle speeds. In general, pedestrians and cyclists often have to share the roadways of residential areas with motorized vehicles, putting them at high risk for accidents due to excessive speed. To cope up with the speeding issues in residential streets, along with enforcement measures (30km/h speed limit), engineering measures such as speed hump have also been used to deal with excessive speeds nowadays.

However, some uncertainties were observed regarding the speed reduction caused by the installed hump. This present dissertation was therefore designed to explore the speeding mechanism on residential streets having 30 km/h speed limit with the presence of a single speed hump along the road by considering the combined effect of street environment or street features and hump. Specifically this research focuses on several purposes like (i) to identify the external factors (based on road geometry) affecting the effectiveness of speed hump; (ii) to investigate the external geometric and non-geometric factors associated with the speed reduction in the upstream of humps; (iii) to identify the suitable position of a single hump to maintain a lower speed along the entire length of the road; and (iv) to predict individual vehicle speed profile of a residential neighborhood where a hump will be installed.

The present dissertation established a relationship between road features and vehicle speed on residential street where a single speed hump is present and the roads having 30 km/h speed limit by developing numerous operating speed models at different locations along the road. Continuous profile-speed data were collected for individual vehicles by using STALKER ATS radar gun from different residential streets in Japan. To investigate the instability of speed reduction caused by the hump as mentioned earlier; this study firstly developed a speed model using multiple linear regression analysis by taking into account the speed at hump location i.e. hump speed as dependent variable. The result shows that,

study street length, presence of intersection and crossing etc. are positively associated with hump speed whereas shape of hump is associated negatively. However, the maximum length of the roads selected for this part of the current research was around 200m which is very small. The speeding behavior might be changed in case of longer road section.

In practical, urban planner should require to understand comprehensively the speed reduction mechanism of a single speed hump in case of a longer road section. Therefore to understand the speed reduction characteristics in a longer road section i.e. 200m to 300m; the present study further developed several speed models at every 10m distance interval in the upstream of humps to investigate the external geometric and non-geometric factors, associated with speed reduction. A total of 500 speed data were collected from 7 different residential streets in Japan. Using multiple linear regression analysis, various road geometric features were found as significant predictors for speed reduction i.e., street marking, road width, two-way traffic, presence of sidewalk etc. A non-geometric factor named “street with many pedestrian” also found significant influence over car speed.

According to the previous studies a single speed hump is effective in reducing vehicle speed at hump location. However, for a safer and livable residential neighborhood, it is important to ensure safe speed throughout the road section not only at hump location. Therefore, the present study is finally established a statistical relationship between the vehicle speed at different distance in upstream as well as downstream of hump and the street features using multiple linear regression analysis. The regression results showed that road width, two-way traffic, one lane, placement of hump etc. had a significant influence on vehicle speed reduction. Furthermore, the developed models were validated with independent data sets. The desired speed trajectory of an individual vehicle of a traffic calmed street can be predicted by using the developed models which help practitioners to find out the optimum placement of a single hump.

On the basis of the above mentioned findings, it can be concluded that the relationship between vehicle speed and the roadway and roadside characteristics developed in this study provide helpful information to the practitioners to understand the speed reduction mechanism of a single hump in case of longer road section (i.e. 200m to 300m) and also help to find out the suitable position of a single hump. The outcome of this study is

meaningful and the authors hope that it can be used to implement and enhance the guidelines and standards of installing hump in such kind of residential streets.

Keywords: *Traffic Safety, Residential Streets, 30 km/h Speed Limit, Speed Hump, Individual Vehicle Speed, Geometric and non-geometric factors.*

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CHAPTER 1

Introduction

1.1 Background

The infrastructures used for connecting different places and mostly for the public services are named as Streets. Streets are also called the cornerstone of a community or a city (Dylan, 2014). Especially, the Residential streets are referred to the streets those have a significant influence on the local environment as well as the local residents. In terms of street function classification, the residential streets are the lowest in order. The purposes of a residential road are to provide access of local traffic, provide on-street parking and last but not the least conveying traffic efficiently. Nonetheless; the primary and main function of a residential street is to provide spaces where the inhabitants' can perform a variety of social activities and to provide a direct access to the adjacent buildings or facilities for pedestrian and bicyclists (Dinh and Kubota, 2013). Therefore, residential streets should be well designed so that the local residents can live and work there now as well as in future also (Department for Transport, 2007).

However, residential streets are now becoming unsafe for the community people because of excessive traffic volume and vehicle speeds (Dinh and Kubota, 2013). In general, pedestrians and cyclists often have to share the roadways of residential areas with motorized vehicles, putting them at high risk for accidents due to excessive speed (driving above the speed limit (Islam *et al.*, 2014)). The relationship between the vehicle speed and the severity of crash injuries have well documented in the past. According to Joksch (1993), fatality risk in a crash increased due to the car speed increased to the fourth power of the original speed.

To minimize the speeding problems in the residential neighborhood, a number of traffic calming measures, such as engineering measures as well as enforcement and education measures have been employed in different countries. For example, a speed limit of 30 km/h has been widely introduced as an enforcement measure in most of the residential streets in Japan. However, in spite of setting the speed limit at 30km/h, excessive speeds are relatively common causing traffic safety problems, which are threatening the livability of neighborhoods in Japan (Dinh and Kubota, 2013). A report by IATSS (2006) highlighted that the percentage of total traffic accidents occurring on residential streets with 30 km/h speed limit has increased to 22.3% in Japan. In an attempt to make the residential areas inherently calmer, along with enforcement measures (30km/h speed limit), engineering measures have also been used to deal with excessive speeds. Different engineering measures such as speed humps, chicanes, shared spaces etc. have been implemented as traffic calming measures in residential areas (Lee et al., 2013). Among the engineering measures, speed humps are the most common traffic calming device (Rahman and Kubota, 2009).

Several types of research have been carried out on the effectiveness of hump. A speed hump is a physical barrier along the road which forces drivers to reduce their speed to 25 km/h while traversing over the device (Tanisha, 2015). Hump effectiveness, to a certain extent, also depends on the shape of the hump. Different shape of humps i.e., Circular, Sinusoidal, Parabolic etc. are found available in residential areas. Among them, "Sinusoidal" hump is the most effective one for noise and vibration reduction (Sayer et al., 1999).

Despite the positive effect of the hump in reducing vehicle speed, the effectiveness of hump is also site-specific. According to the research conducted by Adhikari (2014), it has been found that the speed reduction caused by the installed hump in residential neighborhood in Japan was unstable. The result showed that the average speed at the location of hump varies from site to site. The probable reason of this variation in speed reduction might be the effect of numerous external factors; such as street environment or any other demographic variables or the land uses of residential neighborhood etc. Therefore it is necessary to identify the external factors which may affect the variation of speed reduction on residential streets even after installation of speed hump.

However, residential street should be designed in such a way that it can provide a safe and livable environment to the people living nearside the street. Therefore, speed reduction only at the location of hump is not adequate; it is important to maintain a safe speed along the entire section of the road i.e. at the upstream of device as well as at the downstream. Moreover, in case of longer road section (i.e. 200m to 300m) it becomes very difficult to maintain a lower speed level along the road section by installing a single hump. In such case installing several humps at a regular interval could be an alternate solution yet expensive. Therefore, urban planner should be analyzed the speed behavior of the residential street where speed hump is installed in detail; to make the residential neighborhood safe and sound.

On the other hand, existing literature showed that the street environment itself also has significant influence on vehicle speed reduction (The Highway Capacity Manual, 2000) apart from the effect of any traffic calming devices such as speed hump. For example, the land use patterns of an urban area persuade a reduction in vehicle speed (Wang et al., 2006). According to Elliot *et al*. (2003), the existence of edge marking reduce speed as drivers perceived a decrease lane width for maneuvering. Conversely, a wider road induces drivers to speed up. In addition, non-geometric factors such as road users' activity on road also have significant influence on driving speed (Dinh and Kubota, 2013). To the best of our knowledge, no previous studies specifically focused on such geometric and non-geometric road characteristics on urban residential streets with a 30 km/h speed limit where a single hump is present have been published. This study therefore was designed to find out the suitable position of a single speed hump along a longer road section to maintain a lower speed in the residential neighborhood by analyzing the combine effect of street environment and traffic calming device on vehicle speed.

Moreover, speed humps have been found unsuccessful in some Asian countries unlike American and European countries due to the different road environment and improper guideline for installing hump. While the effectiveness of hump is widely prevalent all over the world, the present study will enhance the guidelines and standards of installing hump in Asian countries having similar road geometry.

1.2 Research Objectives

The primary objective of this research is to investigate the speeding mechanism on urban residential street having 30 km/h speed limit where a single speed hump is present; considering the road geometric and non-geometric features. The objectives are as follows:

(i) To develop a statistical relationship between driving speed and road geometry where a single hump is present

(ii) To evaluate the effectiveness of a single speed hump in case of longer road length

(iii) To identify the suitable position of a single hump to maintain a lower speed along the entire length of the road

(iv) To predict individual vehicle speed profile of a residential neighborhood where a hump will be installed

1.3 Research Contributions

Previous studies were confined to investigate the speed mechanism of urban residential streets having 30 km/h speed limit. This research is the first attempt to explore in-depth speeding behavior on urban streets where a traffic calming device such as hump is present; considering the effect of street environment and a single speed hump. Overall, the outcome of this study can be used to implement and enhance the guidelines and standards of installing hump in Asian countries having such kind of residential streets. Specifically the studies contributions are as follows:

(i) This study identifies the external factors affecting the effectiveness of a single speed hump by taking into account street features and vehicle speed at hump location. The results indicated that hump speed is associated with a variety of roadway and roadside characteristics such as length of street section, shape of hump, presence of intersection or crossing or parking at different distance from hump etc. The findings from this study will provide helpful information to urban planners regarding the installation of hump on urban residential areas having 30 km/h speed limit to make the residential neighborhood more livable and enjoyable.

(ii) This research develops operating speed models at every 10m distance interval in the upstream side of speed hump. A non-geometric factor named “street with many pedestrian” found significant influence over car speed along with the other road geometric factors. The regression analysis further showed that within Zone of Influence (ZoI) area hump is a significant speed reducing factor but outside the ZoI the effect of hump disappear. The results can help practitioners to find out the optimum placement of a single hump along the road section. Furthermore, the speed at the upstream of hump can also be predicted before installation, by using the developed models.

(iii) This dissertation establishes a relationship between the vehicle speed at different distance in upstream and downstream of hump and the street features using multiple linear regression analysis. The regression results showed that road width, two-way traffic, one lane, hump installed along the road etc. had a significant influence on vehicle speed reduction. Furthermore, the developed models were validated with independent data sets. The desired speed trajectory of an individual vehicle of a traffic calmed street can be predicted by using the developed models which help practitioners to find out the optimum placement of a single hump.

1.4 Structure of Dissertation

Chapter 1 discusses the initial background information, and problems which are specifically focused on in this research. Finally, the objectives and contributions of the research are identified.

Chapter 2 provides an overview of residential streets and their speeding problems. The effectiveness of traffic calming devices is also discussed later. This chapter further described the influence of several geometric and non-geometric road features over vehicle speed to dealing with the existing speeding issues on a traffic calmed street in residential neighborhood.

Chapter 3 identifies the external factors affecting the effectiveness of a single speed hump. In this chapter, a statistical relationship is developed between the speed at hump location and the street environment using Multiple Linear Regression equation. The methodology for collecting speed data is also discussed.

Chapter 4 examines the speed reduction characteristics of urban residential streets in the upstream side of speed humps. In this part of the research, several operating speed models is developed at every 10m distance in the upstream of speed hump to describe the influence of external geometric and non-geometric features on driving speed.

Chapter 5 develops a statistical relationship between the vehicle speed in the upstream as well as downstream of hump and the roadway and roadside characteristics. In this chapter, the developed speed models are validated by using independent data sets. The application of the developed models for practical purposes is also discussed later.

Chapter 6 discusses the major findings of this study and provides directions for future research.

CHAPTER 2

Speeding Problems on Residential Streets

2.1 Introduction

Residential streets or neighborhood streets in particular, are pedestrian-oriented (Grannis, 1998); providing convenient access to homes for all road users and adequate spaces where local residents can assemble (Neighborhood Street Design Guidelines, November 2000). These streets are referred to the streets those have the lowest ranking in terms of street function classification. Ideally, neighborhood streets are designed to minimize through traffic and efficiently serve the local traffic and local residents. A report by The Institute of Transportation Engineers highlighted that; residential streets should be designed in such a way that it can ensure traffic safety for both vehicle and pedestrian and also encourage drivers to drive slowly over the road (Joseph).

However in residential neighborhood, traffic safety has become the prime issue nowadays both in real and in perceived. A survey conducted by York *et al*. (2007) revealed that, within the residential area the main concern of the peoples is the danger of road traffic. The positive effects of traffic encourage residents to involve in physical outdoor activities more whereas the negative effects cause traffic accidents and also hinder the enjoyment of living in that area (Dinh and Kubota, 2012). According to Cerin *et al*. (2007), within the residential neighborhood where residents like to walk, crash risk was negatively associated with their perception. Furthermore, in terms of perceived risk, researchers found that the residents' perceived crash risk increased with increasing traffic volume and car speed (Dinh, 2013).

According to the study stated above it is clear that excessive speeds are inappropriate in residential areas (OECD/ECMT, 2006). The road users living nearby the residential-street often have to share the roadway with motorized vehicles, perceived higher risk for an accident due to excessive speed.

2.2 Speeding Problems in Residential Streets

Speeding is a significant traffic safety problem in neighborhood streets. Obviously, increasing speed is the reason for increase fatality as well as crash injuries. According to Bottlinger (2017), in a residential neighborhood; 5% pedestrian will die if hit by a car at a traveling speed of 30km/h; whereas 45% and 85% pedestrian will die at a traveling speed of 50km/h and 60km/h, respectively. In the case of the child, the likelihood of death is even higher. Not only the death but also the severity of pedestrian injuries is strongly related to higher speed (Zainuddin *et al.*, 2013). A report by the World Health Organization (2004) highlighted that 1 km/h increase in average speed will increase the risk of crash injuries by 3%.

Furthermore, fatal accidents were most often caused in the mid-speed range i.e. between 30 and 60 km/h (ITARDA, 2011), which is the posted operating speed in residential streets (Shahram *et al.*, 2014). Figure 2.1 illustrates the number of fatalities involved in a car accident within a speed range of 30 to 60 km/h.

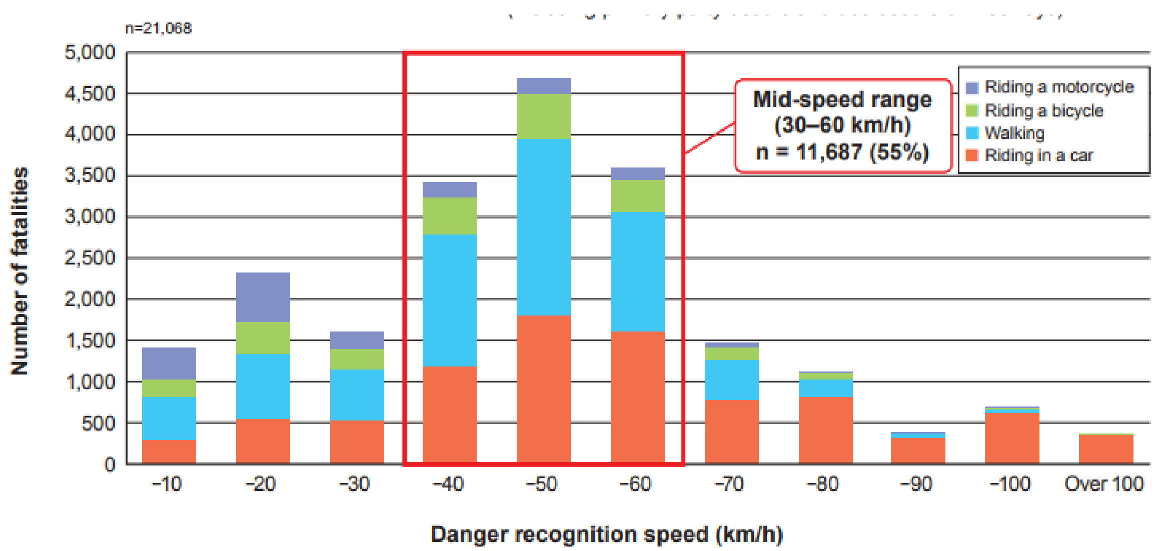
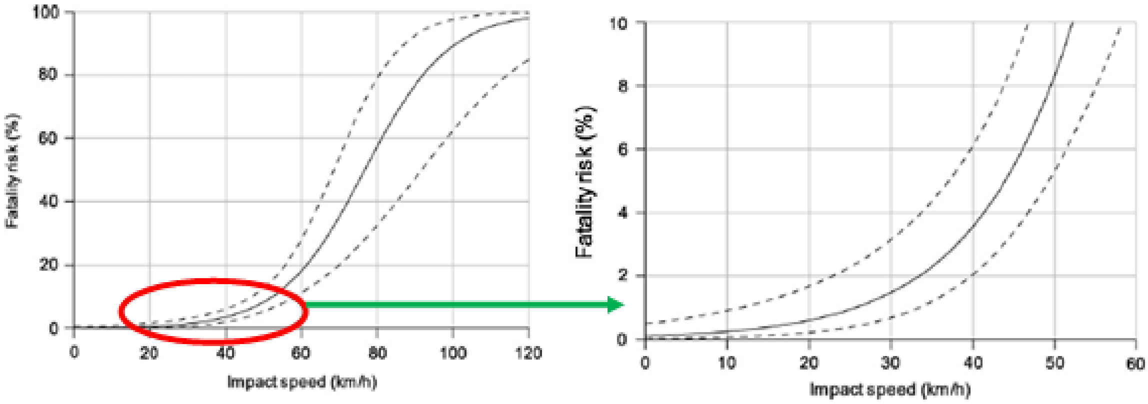


Fig. 2.1:Number of fatalities by speed and means of transportation (ITARDA 2011)

Rosen and Sander (2009) analyzed the casualty risk of adult pedestrian as a function of impact speed hit by a car and the results showed that the fatality rate increases with increasing impact speed. Figure 2.2 represents the pedestrian fatality risk where the dotted curves show approximate 95% confidence limits.



(a) The fatality risk as a function of impact speed for adult pedestrians hit by the front of a passenger car

(b) Zoom in on the risk curve below 60 km/h.

Fig. 2.2 Pedestrian fatality risk
(Rosen and Sander, 2009)

However, speeding issues in urban residential streets to a certain extent also depends on the street environment. A study conducted by The Danish Accident Investigation Board based on 99 accidents due to excessive speeding and interviews of 38 driver, revealed that the road features such as wider lanes, presence of central reserve and multiple lanes encourage drivers to choose higher speed whereas, rigid obstacles, steep slopes, narrow shoulders and the number of road entrance induce drivers to slow down (Andersen *et al.*, 2016). According to Lobo *et al*. (2013), intersections density in the upstream of a road reduces vehicle speed. Similarly, car speed increases if centerline or edge road marking is present on road rather than no markings. The possible explanation might be that roads with markings often represent the wider road and having good maintenance-level which increase driver's perception of safety and drive faster (Andersen *et al.*, 2016). Furthermore, with respect to the road type, the number of accidents on residential roads with road width of 5.5 m or less than accounted for 25.30% of all accidents in Japan in 2007. Although, recently this rate had a slightly decreasing trend however it still accounted for 24.78% of all accidents in the year 2011.

Table 2.1 Number of Accidents by Road Width in Japan

Road Width	Year					
	2004	2005	2006	2007	2010	2011
Less than 3.5m	45903	43643	42012	22123	21921	21310
3.5m-5.5m	162232	161913	155631	55685	46339	44481
Intersection area(road width under 5.5m)	-	-	-	132781	113165	105664
Sub-Total	208135	205566	197643	210589	181425	171455
Sub-Total (%)	21.86	22.01	22.29	25.30	25.00	24.78
Total in all Streets	952191	933828	886864	832454	725773	691937

Note: Before 2007, the numbers of accidents at intersection categories were included in the figures of other categories by road width (Source: Traffic Accident Statistics published annually by Traffic Bureau of National Police Agency (Japan))

The facts about traffic accident situation in Japan clearly suggest that more attention should be paid on accidents with pedestrians/cyclists involved to obtain sustainable traffic safety. Because the accidents in minor roads such as residential streets accounted for a high percentage of all crashes, neighborhood streets are therefore indicated as the promising areas for enhancing the traffic safety in Japan.

Besides the real traffic accidents, residential areas in Japan are also facing other traffic problems such as excessive driving speeds and traffic volume. Requests on the neighborhood traffic problems are very common that often put local governments at hard tasks to enhance the safety and livability of residential areas.

2.3 Traffic Calming Measures

A report jointly published by the Institute of Transportation Engineers (ITE) and the Federal Highway Administration (1999) defined traffic calming as “Traffic calming involves changes in street alignment, installation of barriers, and other physical measures to reduce traffic speeds and cut-through volumes in the interest of street safety, livability, and other public purposes”. Traffic calming measures have been used as a countermeasure for traffic safety issues in many countries such as USA, Australia, and European countries.

According to Zein *et al*. (1997), traffic calming reduced collision frequency by 40%, vehicle insurance claims by 38%, and fatalities from one to zero.

Mostly, two types of traffic calming measures have been considered worldwide.

1) Enforcement and education measures
2) Engineering measures

To cope up with the speeding issues in residential streets, 30 km/h speed limit has been introduced as an enforcement measure which is found unsuccessful in many countries such as Japan. A report by IATSS (2006) highlighted that the percentage of total traffic accidents occurring on residential streets with 30 km/h speed limit has increased to 22.3% in Japan. Figure 2.3 illustrates the cumulative distribution of mean speeds at the accident locations.

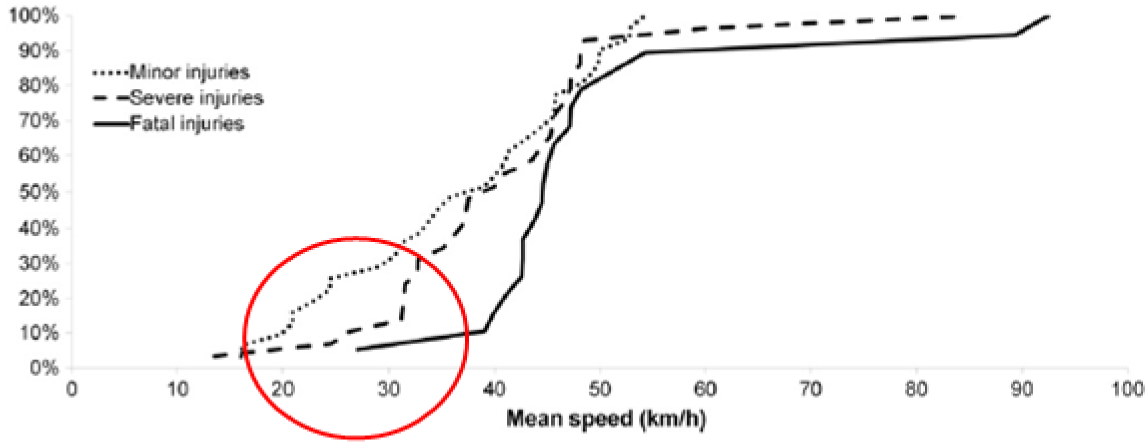


Fig. 2.3 Cumulative distribution of mean speeds at the accident locations by injury severity group

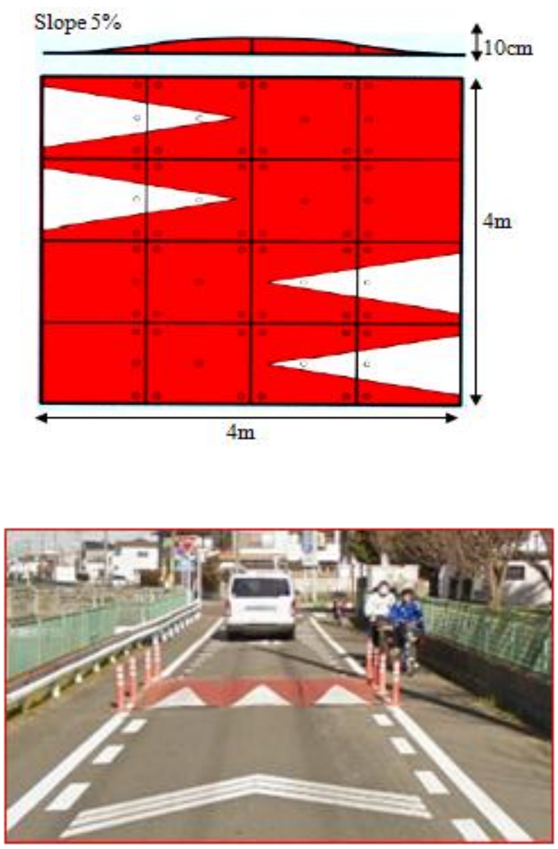
(Kröyer, 2015)

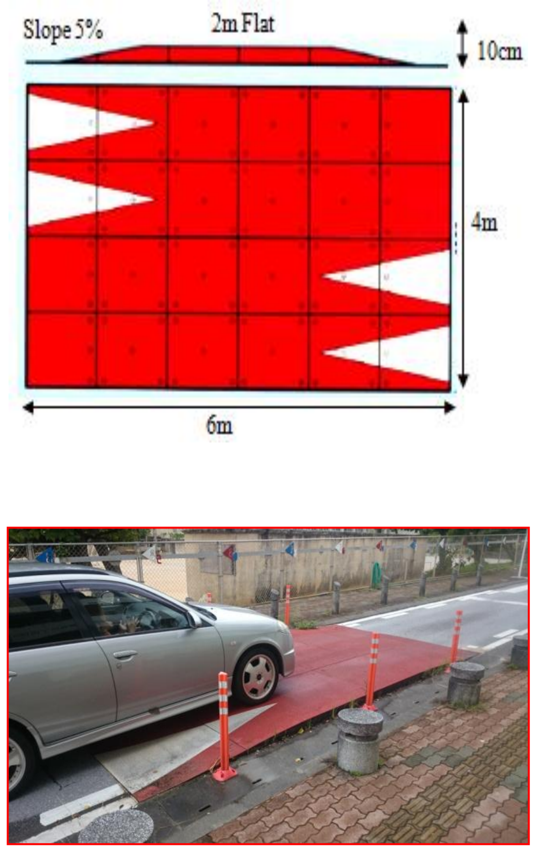
From the above figure it is the evident that the risk of severe injuries increases exponentially after the speed exceeds 25 km/h, which indicated that posting 30 km/h speed limit, is not sufficient to maintain lower speed throughout the road section.

Therefore, it is necessary to install any physical measure or engineering measures such as speed hump along with the enforcement measures (posted speed limit or 30 km/h speed limit) to reduce vehicle speed along the road (Pau and Angius, 2001).

2.4 Speed Hump

Speed humps have been known as traffic calming devices that can be used to effectively reduce speeding problems. In the previous research it has been proved that vehicle speed reduces after using hump. According to Bachok *et al*. (2016), a speed hump can reduce the 85th percentile vehicle speeds significantly, with speed reductions ranging from 10 to 16 km/h. The main function of a speed hump is to force drivers to reduce their speeds while passing over the device (Roess, 2004). Different shape of humps i.e., Circular, Sinusoidal, Trapezoidal etc. are found available in residential areas. Figure 2.4 shows the picture of different types of hump





(a) Bow Shape Hump (b) Top-Flat Hump

Source: Kojima et al. (2011)

(c) Trapezoidal hump or Speed Table

(https://images.app.goo.gl/FnthowyyKUCrd1ns7)

Fig. 2 4 Picture of different types of hump

2.5 Effectiveness of Speed Hump

The effectiveness of speed hump in reducing vehicle speed and traffic accidents in a residential street is widely prevalent in all over the world. A study conducted by Dinh *et al*. 2013, calculated the mean speed of each vehicle before and after installation of speed hump. The research concluded that mean speed of all vehicles become lower after installing hump in urban residential street.

Table 2.2 Descriptive statistics of speed indicators

Indicators	Before experiment		During experiment		Mean speed reduction (km/h)	Mean speed reduction (%)
	Vmean	V85th	Vmean	V85th		
Section 1						
Maximum speed within subsection 1	44.63	50.33	42.60	47.07	2.03	4.56
Maximum speed within subsection 2	47.55	53.32	45.04	51.23	2.50	5.26
Speed at hump location	37.80	43.17	23.60	36.08	14.20	37.58
Section 2						
Maximum speed within subsection 1	49.65	55.83	42.93	47.59	6.72	13.54
Maximum speed within subsection 2	50.15	58.04	46.03	52.74	4.12	8.21
Speed at hump location	49.07	55.29	19.47	26.55	29.59	60.32

From table 2.2 it is proved that, vehicle mean speed has been reduced by 4.56% after installing hump along the road.

LaToya (2004) compared speed humps with two traffic calming devices, the speed slots and speed cushion. The findings revealed that speed humps recorded the lowest crossing speed and relatively high frequency of braking maneuvers compared to speed slots. Furthermore, among the different shapes of hump, “Sinusoidal” hump is the most effective one for noise and vibration reduction (Kojima *et al*., 2011).

On the other hand, Ndhlovu (2013) studied the effectiveness of traffic calming in reducing road carnage in Masvingo using qualitative and quantitative data. The research found that the numbers of road accident were reduced by 3-63%, fatality by 4-36% & injury 4-70% where humps were installed and 5.9% reduction in road carnage where speed tables were used.

2.6 Research Hypothesis

From the discussion stated in the above sections it is clear that speed hump is an effective traffic calming measure in vehicle speed reduction in residential neighborhood. However, the street environment of the urban areas somewhat also has significant influence on vehicle speed reduction. Therefore it is necessary to examine the speed reduction mechanism in residential streets in detail considering both the effect of roadway and roadside characteristics and speed hump over car speed to combat with the traffic safety problems in such kind of areas.

The current dissertation considered the vehicle speed at different section along the road where speed hump is present as a dependent variable and road features as an independent variable for developing speed models. The research hypothesis regarding the effect of road geometric factors over car speed are described below:

(i) Road Length

Representing the total length of street section along which study has been conducted. It is the length between the starting point and ending point of survey. A longer length resulted in higher values for speed because the longer length provided more space for acceleration. So length of street section is an important geometric factor for calculating speed.

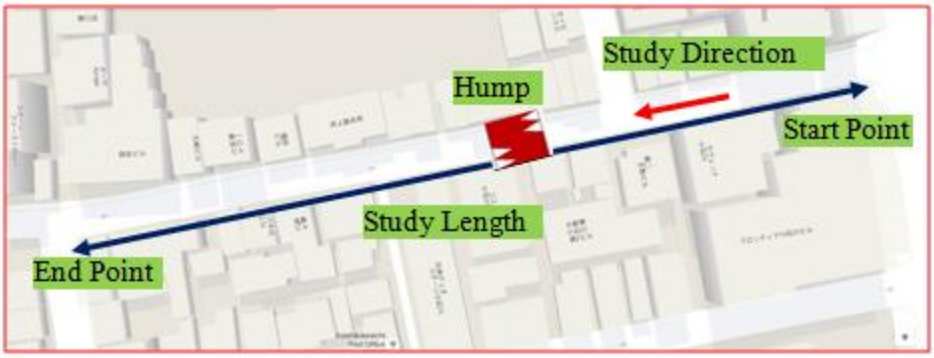


Fig. 2.5 Road length

(ii) One Lane

It indicates the roads having a single lane for traffic in both directions; when vehicles meet one must pull off the road to let the other pass (web site-cited in 3rd June, 2019). As per definition it can be said that number of lane is closely related to speed of car. If roadway width is narrow and traffic direction is two-way then drivers must be cautious about the speed during driving.

Fig. 2.6 One lane

(iii) Sidewalk

A sidewalk (American English) – also known as a footpath, footway or pavement, is a path along the side of a road (web site-cited in 3rd June, 2019). A sidewalk may accommodate moderate changes in grade (height) and is normally separated from the vehicular section by a curb. Sidewalks play an important role in transportation, as they provide a safe path for people to walk along that is separated from the motorized traffic. Generally, a sidewalk on both sides means that vulnerable street users would be less likely to be in the roadway. This could give drivers an increased perception of safety, leading them to choose a higher speed. But in this research the selected study sections are completely exists on residential areas. So residents nearby the roads feel free to use the road as well as sidewalk. So during driving in these areas driver should be careful about speed to avoid conflict.

One Sided Sidewalk   Both Sided Sidewalk

Fig. 2.7 Sidewalk

(iv) Two-way Traffic

A two-way street is a street that allows vehicles to travel in both directions. On most two-way streets, especially main streets, a line is painted down the middle of the road to remind drivers to stay on their side of the road. Sometimes one portion of a street is two-way, the other portion one-way. If there is no line, a car must stay on the appropriate side and watch for cars coming in the opposite direction and prepare to pull over to let them pass (web site-cited in 3rd June, 2019). In this study most of the selected street sections have one lane and two-way traffic which make the streets narrower than usual. So drivers have to pay attention on their speed during pass opposite car on these types of roads.

Fig. 2.8 Two-way traffic on one lane road

(v) Presence of Intersection or Crossing or Parking or Pedestrian Entry

A study done by Dinh and Kubota (2013) showed that mean speeds at 3-leg intersections were higher than that at 4-leg intersections. It means that presence of any unsignalized T intersection on the study street affect the driving speed. Similarly the car speed also affect by the presence of crossing, parking and any other entry point from where pedestrian comes on road directly and cross the road without using crossing.

Presence of T

Presence of Crossing

Presence of Parking

Presence of pedestrian Entry Point

Fig. 2.9 Presence of T intersection, Crossing, Parking and Pedestrian entry point

(vi) Distance Between Intersection/Crossing/Parking/Entry Point from Hump

According to hypothesis, if the distance between intersection or crossing or parking or entry point is short or small i.e. 10m or 20m (Johansson, 2011) then drivers must reduce their speed. But if the distance is longer or greater i.e. 60m or 70m then driver does not consider speed. They just drive on their original speed. Because in such case, through traffic has the priority to go first.

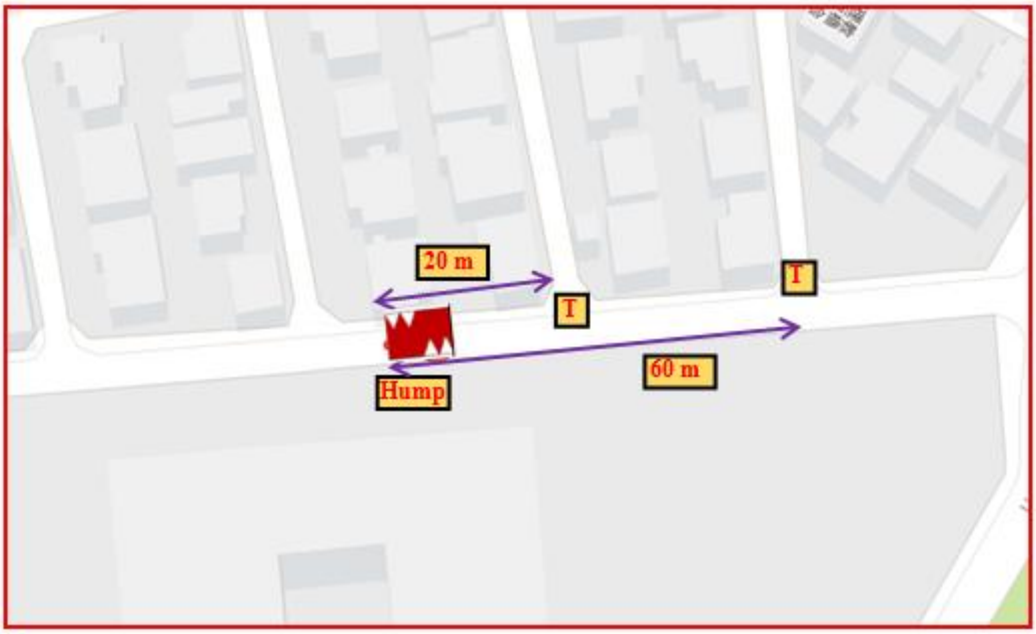


Fig. 2.10 Presence of T intersections at different distance from hump

CHAPTER 3

Hump Speed and Street Characteristics

3.1 Introduction

Previous research has been extensively described the effectiveness of speed hump in reducing vehicle speed as well as traffic accidents in a residential neighborhood (Kamada *et al.*, 2015).

However, the effectiveness of hump is site-specific. Research based on evaluating the effectiveness of speed hump in 7 different urban residential streets in Japan concluded that the average speed and the 85th percentile speed at the location of hump varies from site to site and this variation is inconsistent (Adhikari, 2014). The mean speed and the 85th percentile speed of all seven study sites have been compared by the Author which is shown in Figure 3.1 and 3.2 graphically.

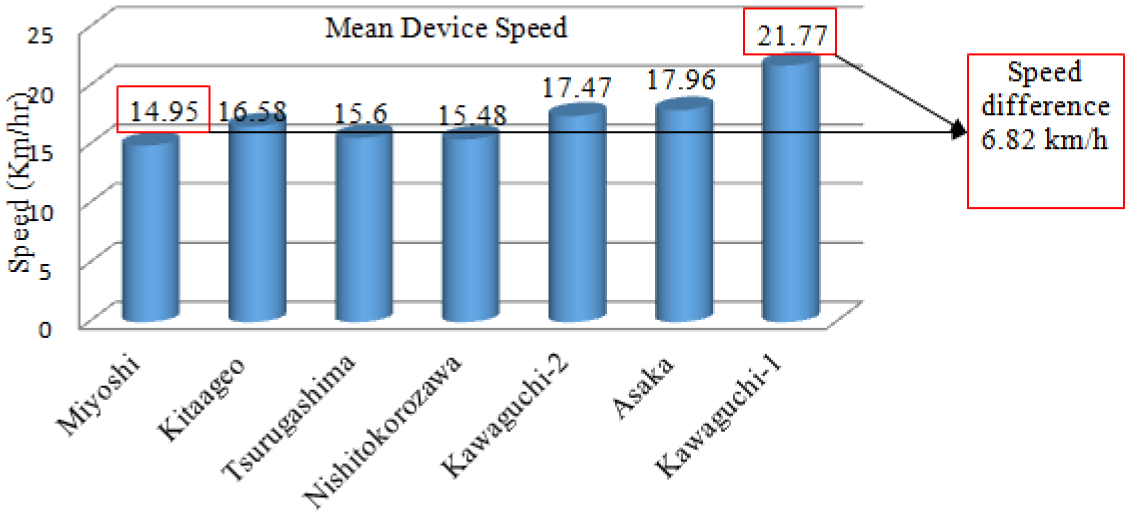


Fig. 3.1 Mean Speed at device location of different sites

(Adhikari, 2014)

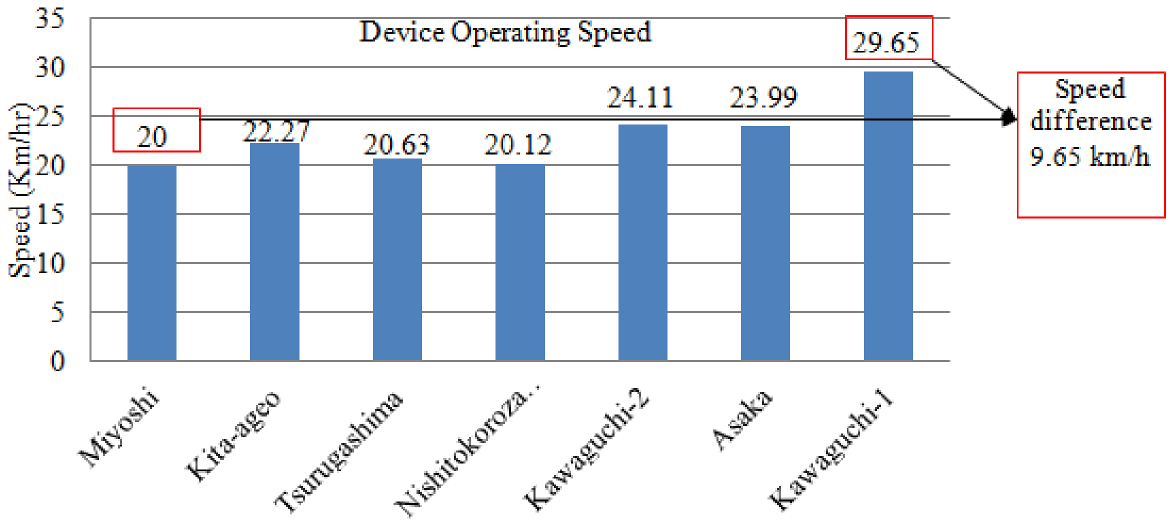


Fig. 3.2 Operating speed at device location of different sites

(Adhikari, 2014)

From the above figures, it is the evident that the mean speed and the 85th percentile speed at hump position vary from location to location, though; all of the streets were located in urban residential areas having 30 km/h speed limit and the hump shape was same in all the locations. Probably, this variation in the speed reduction influenced by numerous external factors such as street environment, road geometry, landscape of residential neighborhood, or other demographic variables etc.

Existing literatures showed that different road geometric features have significant influence on car speed. According to Wang *et al*. (2006), drivers speed choice to a certain extent depends on the street environment. The developed speed models revealed that presence of sidewalk, on-street parking, and roadside density has negative effect on driver's speed choice, whereas number of lane, land use of residential neighborhood has positive effect. Another study investigated the effect of road features on vehicle speed in urban roads illustrated that width of lane, and roadside characteristics has significant influence over car speed (Poe and Mason, 2000). Similarly, a study estimated the operating speeds for urban residential streets with a 30 km/h speed limit using profile speed data concluded that a longer length resulted in higher values for speed (Dinh and Kubota, 2013). Furthermore, a study conducted by Tarris *et al.* (1996) demonstrated that T intersection density along the tangent section of urban street reduces car speed.

Previous studies were limited to describe the influence of road features on car speed in urban streets only. No study discussed about such kind of speed behavior in residential neighborhood after installing speed hump. Therefore, it is necessary to identify the effect of roadway and roadside characteristics on car speed in residential streets having 30 km/h speed limit where hump is present.

3.2 Study Objective

The objective of this part of the current dissertation is to identify the external factors (based on road geometry) affecting the effectiveness of speed hump. For this study continuous speed data were collected from 20 different residential streets in Japan to develop operating speed model at hump location. The models were developed using multiple linear regression analysis. A total of 400 speed data were collected in free flow condition for modeling purpose.

3.3 Methodology

The methodology of this chapter is shown in the following framework

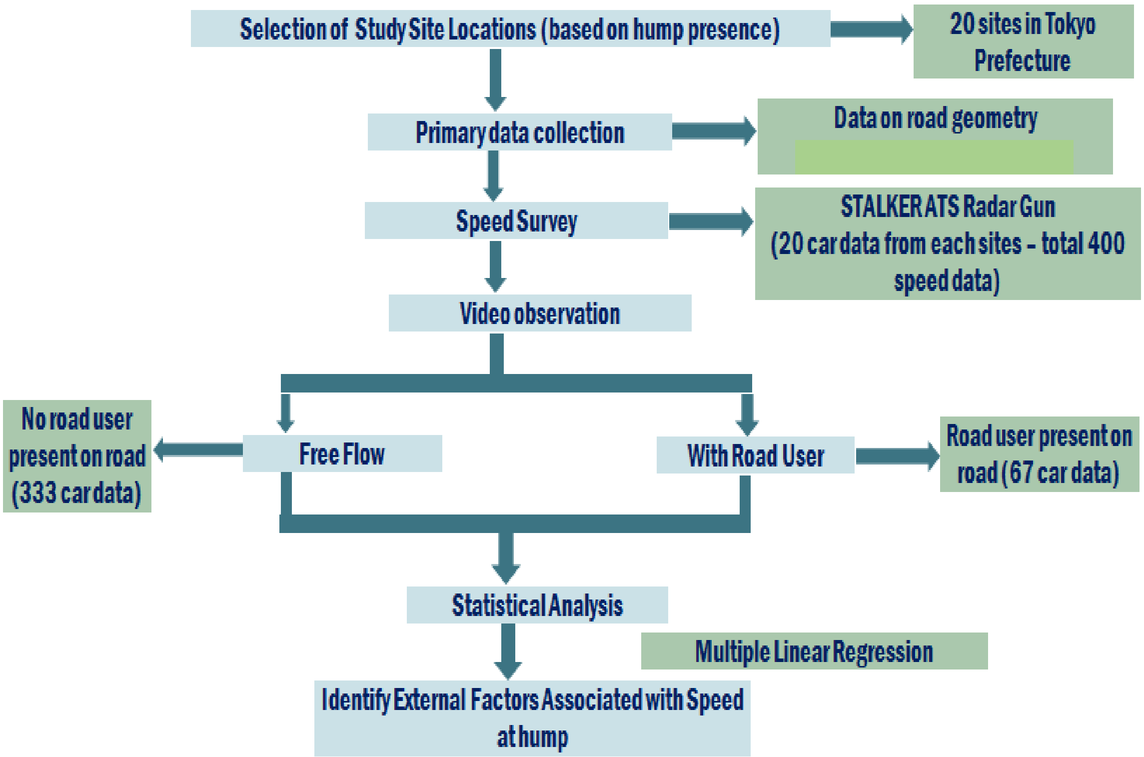
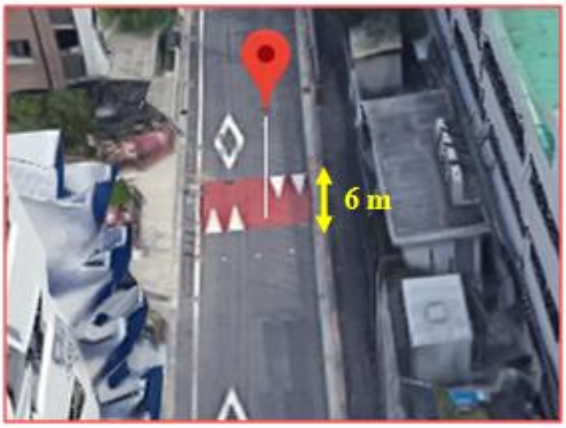


Fig. 3.3 Conceptual framework for analysing hump speed

3.4 Data Collection

Continuous speed data were collected for individual vehicles by using STALKER ATS radar gun on 20 different residential streets in Tokyo Prefecture in Japan. Among these, 2 were located in Bunkyo city, 8 were in Fuchu and another 10 were in Higashimurayama city. Speed data collection period was from 18th December 2015 to 10th June 2016 in daytime from 9.00 am to 5.00 pm. Naturally, two types of hump (sinusoidal and trapezoidal) were found in the study locations but for detail analysis of the speed behavior at hump location; the trapezoidal hump has been considered as two category based on the length of top portion of hump i.e. Trapezoidal hump 1 (top length - 8 to 13 m) and Trapezoidal hump 2 (top length – 14 to 20 m). Figure 3.4 shows the shape of the humps found in study sites.



Sinusoidal Hump

(35°42'51.5"N 139°45'00.1"E)

Trapezoidal Hump 1

(35°44'55.8"N 139°27'16.6"E)

Trapezoidal Hump 2 (35°40'50.0"N 139°28'35.5"E)

Fig. 3.4 Types of hump found in study locations

[Source: Google Map (2019)]

3.4.1 Site selection

Straight street sections, where humps have been installed, were selected for this study. All of the selected sites were located in residential areas with a speed limit of 30 km/hr. The selected street section is used as a connecting road with two arterial roads. In Bunkyo and Higashimurayama city, all the selected locations are busy with pedestrian activities along the road because of the presence of the elementary school and park or playground nearby the study roads. On the other hand, the streets in Fuchu are thoroughly located in residential neighborhoods having different housing apartment or kid's playground along the both sides of the streets. Furthermore, the street sections selected for this study must contain different road geometric features such as sidewalk, street marking, the presence of T intersection or parking or crossing, etc. The total length of the selected roads varied between 60m to 200m where the hump is located in the middle position or close to the middle portion of the total study length.

3.4.2 Street features

Different geometric features associated with the study sections were recorded, including sidewalk width, street marking, intersection or parking or crossing density, etc. Table 3.1 summarized the description of the selected road sections.

Table 3.1 Summary of selected street section characteristics

Street Indices	Description	Measured value
Street Section	Length of Street Section (m)	63.15 to 194.49; mean: 127.87
	No of Lanes	1 to 2; mean: 1.15
	Lane Width (m)	2.55 to 4.35; mean: 3.89
	Carriageway Width (m)	2.97 to 5.12; mean: 4.26
	Roadway Width (m)	4.43 to 7.26; mean: 5.29
	Left Safety Strip Width (m)[a]	0.5 to 1.08; mean: 0.57
	Right Safety Strip Width (m)[b]	0 to 1.08; mean: 0.45
	Street Marking	No Marking: 15 sites; Edge Marking only: 3 sites; Edge and Centre Marking: 2 sites
Sidewalk Condition	Presence of Sidewalk	No Sidewalk: 0 sites; Sidewalk on one side: 17 sites; Sidewalk on both side: 3 sites
	Sidewalk Width (m)	1.3 to 3.6; mean: 2.42

Table 3.1 Summary of selected street section characteristics

Street Indices	Description	Measured value
T Intersection	No. Of T Intersection	Before Hump: 3 sites After hump: 1 site At Hump: 5 sites Both side of Hump (before and after): 7 Sites No T Intersection: 4 sites
	Distance between Target Hump and T Intersection (Before hump) [c] (m)	0-10m: 5 sites; 10-20m: 2 sites; 20-30m: 2 sites; 30-40m: 3 sites; 40-50m: 1 site; 50-60m: 2 sites; 60-70m: 2 sites
	Distance between Target Hump and T Intersection (After hump) [d] (m)	0-10m: 4 sites; 10-20m: 1 site; 20-30m: 1 site; 30-40m: 2 sites; 40-50m: 1 site; 50-60m: 0 sites; 60-70m: 0 sites; 70-80m: 0 sites; 80-90m: 0 sites;90-100m: 1 site
Parking Condition	No of Parking	Before Hump: 4 sites After Hump: 4 sites Both side of Hump (before and after): 3 Sites No Parking: 9 sites
	Distance between Target Hump and Car Parking (Before hump) [e] (m)	0-10m: 1 site; 10-20m: 0 sites; 20-30m: 2 sites; 30-40m: 1 site; 40-50m: 0 site; 50-60m: 0 sites; 60-70m: 1 site; 70-80m: 1 site
	Distance between Target Hump and Car Parking (After hump) [f] (m)	0-10m: 1 site; 10-20m: 2 sites; 20-30m: 2 sites; 30-40m: 0 sites; 40-50m: 0 site; 50-60m: 0 sites; 60-70m: 0 sites; 70-80m: 0 sites; 80-90m: 0 sites;90-100m: 1 site
Crossing	No of Road Crossing	Before Hump: 5 sites After Hump: 2 sites At Hump: 5 site No Crossing: 8 sites
	Distance between Target Hump and Road Crossing (Before hump) [g] (m)	0-10m: 0 site; 10-20m: 3 sites; 20-30m: 1 site; 30-40m: 0 site; 40-50m: 0 site; 50-60m: 1 site
	Distance between Target Hump and Road Crossing (After hump) [h] (m)	0-10m: 1 site; 10-20m: 1 site; 20-30m: 0 sites; 30-40m: 1 site
Pedestrian Entry	No of Pedestrian Entry Point[i]	Before Hump: 3 sites After Hump: 3 sites At Hump: 2 sites Both side of Hump (before and after): 1 site No Crossing: 11 sites
	Distance between Target Hump and Pedestrian Entry Point (Before hump) [j] (m)	0-10m: 1 site; 10-20m: 0 sites; 20-30m: 0 site; 30-40m: 0 site; 40-50m: 2 sites; 50-60m: 1 site
	Distance between Target Hump and Pedestrian Entry Point (After hump) [k] (m)	0-10m: 1 site; 10-20m: 2 sites; 20-30m: 0 site; 30-40m: 0 site; 40-50m: 0 sites; 50-60m: 1 site

Table 3.1 Summary of selected street section characteristics

Street Indices	Description	Measured value
Traffic Condition	Traffic Direction	Two way Traffic: 19 Sites; One way Traffic: 1 Site
Hump	Hump Shape	Sinusoidal Hump: 2 sites Trapezoidal 1 (length 8-13m): 13 sites Trapezoidal 2 (length 14-20m): 5 sites

Notes: [a]Left Safety Strip Width (m)- Distance between the edges of a study lane to the curb on the left side of target direction. [b]Right Safety Strip Width (m) - Distance between the edge of a study lane to the curb on the right side of target direction. [c]Distance between Target Hump and T Intersection (Before hump)(m)– It is the distance between T intersection and Hump where the T intersection must exist before hump and within study street section. [d]Distance between Target Hump and T Intersection (After hump)(m) - It is the distance between T intersection and Hump where the T intersection must exist after hump and within study street section. [e]Distance between Target Hump and Car Parking (Before hump)(m) - It is the distance between Car Parking and Hump where the Parking must exist before hump and within study street section. [f]Distance between Target Hump and Car Parking (After hump)(m) - It is the distance between Car Parking and Hump where the Parking must exist after hump and within study street section. [g]Distance between Target Hump and Road Crossing (Before hump)(m) - It is the distance between Road Crossing and Hump where the Crossing must exist before hump and within study street section. [h]Distance between Target Hump and Road Crossing (After hump) (m) - It is the distance between Road Crossing and Hump where the Crossing must exist after hump and within study street section. [i]No of Pedestrian Entry Point - It is the point from where pedestrian directly comes on road and possibility to cross the road without using crossing (such as from any park or building etc.). [j]Distance between Target Hump and Pedestrian Entry Point (Before hump)(m) - It is the distance between Pedestrian entry point and Hump where the point must exist before hump and within study street section. [k]Distance between Target Hump and Pedestrian Entry Point (After hump)(m) - It is the distance between Pedestrian entry point and Hump where the point must exist after hump and within study street section.

3.4.3 Speed data measurement

In this study, a STALKER ATS radar gun, connected to a laptop, was used to record individual vehicle’s traveling speed continuously. However, in-vehicle devices such as GPS or dashboard cameras or CAN data are also effective in collecting continuous speed data (Wang *et al.*, 2006; Zuriaga *et al.*, 2010) but these devices are mainly used for experimental research. The present research is an observational study. In addition, driver speed behaviors also affected by installing devices on their vehicle. Therefore, STALKER ATS radar gun has been used for recording free flow speed data in this study.

Driving speeds were measured in free flow condition which indicates that during the data collection period, only the target vehicle appeared on the study street section and there was very little interference of other moving objects like vulnerable road users on the roadway at the same time. In the case of high interference, a cut-off speed of 8 km/h was set up for the radar gun. It means that, if the speed of target vehicle was interrupted by the speed of less than 8 km/h which may be caused by other moving objects like pedestrian or cyclists had been eliminated from the target vehicle's speed data. Radar gun started to record speed data when a target vehicle entered into the study section and was then keep operating until the vehicle reached the end of the study section. The gun and surveyor were always located about 5m behind the entry point of the street section and were carefully hidden behind in or under objects to avoid the unfavorable situations that may occur in the site with the drivers. To enhance the accuracy of speed data, the radar gun was set up on the same side of the study lane. Figure 3.5 shows the procedure of speed data collection in field including the position of surveyors and video cameras.

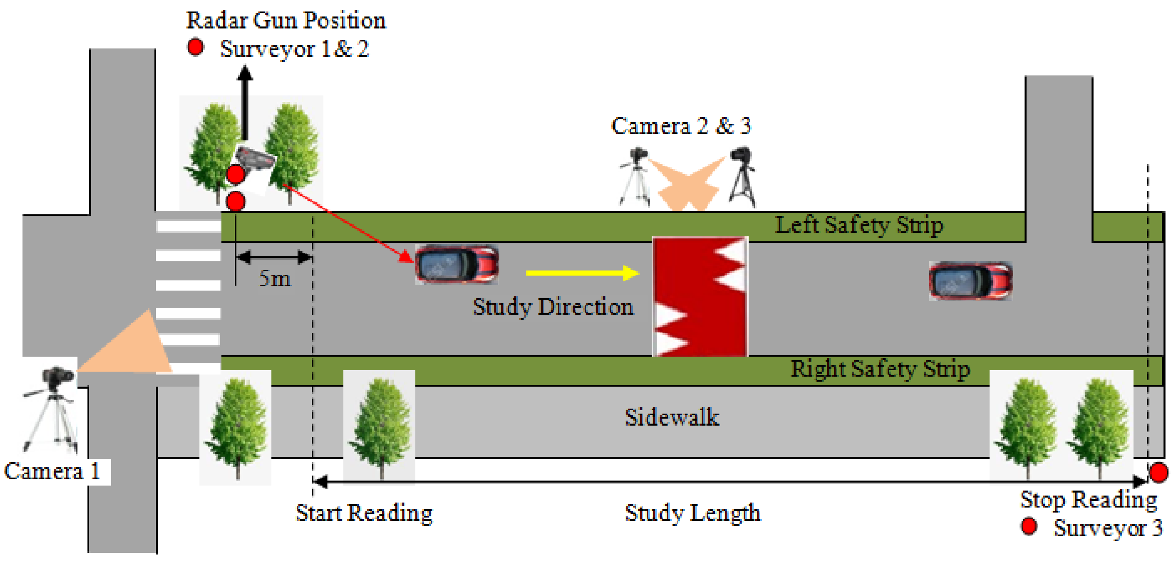


Fig. 3.5 Field data collection

At least 20 profile speeds were collected for each study sites and data were collected during the daytime only in good weather condition. This study measured the speed of passenger cars and light trucks only. In total 400 car data were collected from all study locations.

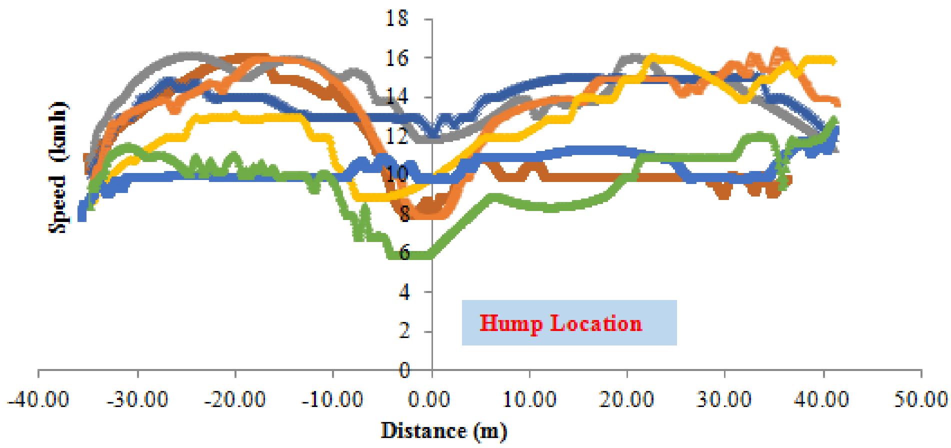
3.4.4 Recording of video data

A video survey was carried out in order to ensure a free flow condition. Through video observation, the movement of the target vehicles was verified whether it was disturbed by the other road users (like pedestrians or cyclist, opposite cars, etc.) or not. As illustrated in

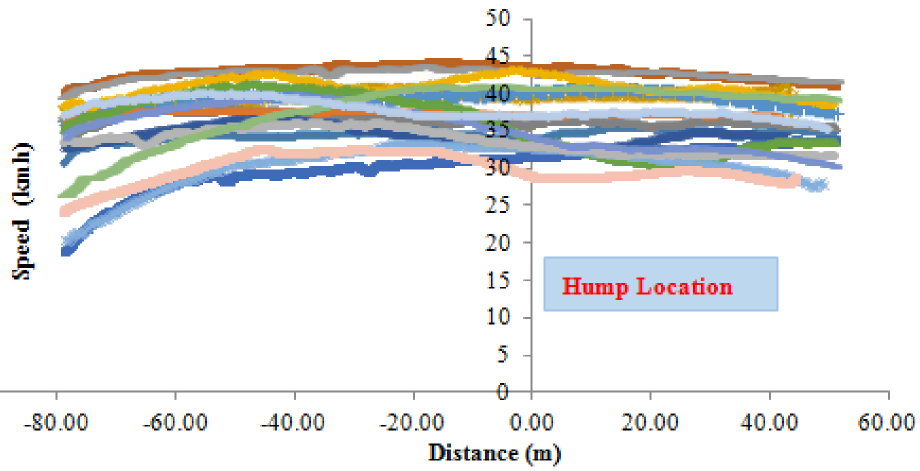
Figure 3.5, three video cameras were installed in the study site. One camera recorded vehicular movement from backward direction and was set up at the entry point of the study road. Another two cameras were installed at the hump location in opposite direction to each other to cover the full study street length. For vehicle speed measurement, three surveyors were involved. Surveyor 1 operated radar gun and Surveyor 2 recorded the speed data in laptop and also noted down the vehicle plate number simultaneously. At the endpoint of the study section, Surveyor 3 recorded the target vehicle's detail with the plate number. The vehicle plate number recorded by Surveyor 2 and 3 was rechecked later to ensure the exact target vehicle. From the video record, the interaction between the target car and the vulnerable road users were checked and eliminated from the final set of data. Finally, free flow speed data of target cars were taken for further analysis.

3.4.5 Data filtering

Speed data were processed in the laboratory using software program accompanied by STALKER ATS radar gun. To create a speed profile, the processed data were used along with the information on street layout features. Figure 3.6 shows the typical speed profile data for two types of hump of some of the vehicles in one street section. Herein, the distance at the hump location is set to zero while the negative (-) and positive (+) sign of distance indicates the upstream and downstream side of hump respectively.



(a) Sinusoidal Hump



(b) Trapezoidal Hump

Fig. 3.6 Typical speed profiles of two types of hump

The above figures clearly showed that the vehicle speeds were lower at hump location in case of sinusoidal hump however in case of trapezoidal hump no significant difference was observed between the speed at hump location and the upstream or downstream of device. In this case, hump location was verified from the video recording using the video camera's time and target vehicle's approaching time at hump location. Speed profiles with abnormal driving patterns (i.e. on-street parking or car which did not complete the full study length etc.) were excluded. After data reduction, a total of 333 individual speed profiles in free flow conditions for 20 locations remained for further analysis.

3.5 Data Analysis

3.5.1 Comparison of mean speed profile of three types of hump

The mean speed profile of three types of hump has been presented below:

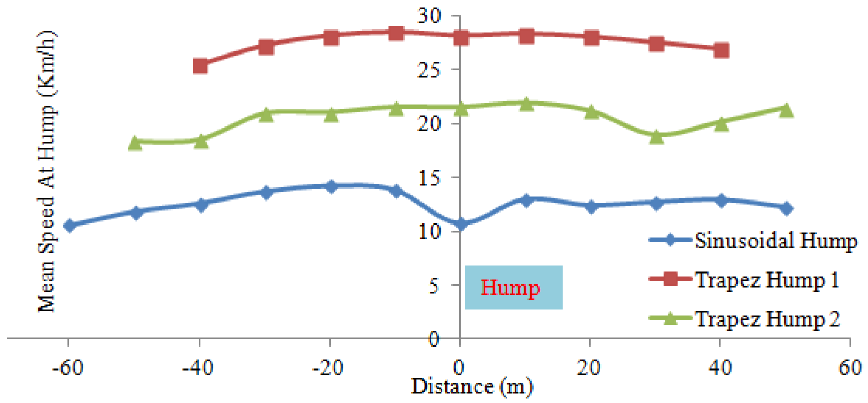


Fig. 3.7 Mean speed profile of three types of hump

From figure 3.7 it is the evident that Sinusoidal hump is more effective in reducing speed than Trapezoidal humps.

3.5.2 Model development

This part of the current dissertation developed the operating speed models at hump location using Multiple Linear Regression analysis. This type of analysis applies when several predictor variables such as x, x_1, x_2, $x_3 \ldots x_n$ exists. The general form of Multiple Linear Regression is shown in Equation (1):

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots\ldots + \beta_k x_k + \varepsilon \qquad (1)$$

Where, Y is the dependent variable; x_1, x_2, $x_3 \ldots x_n$ are the independent predictor variables; β_0, β_1,$\beta_2 \ldots \beta_k$ are unknown regression coefficients, and ε is the random error.

In the current study, the logarithmic form of the dependent variable has been taken to establish a linear relationship between the dependent and independent variables as well as to reduce the influence of "heteroscedasticity". The model form is as follows:

$$\ln Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots\ldots + \beta_k x_k + \varepsilon \qquad (2)$$

Wherein,

Y = vehicle speed at hump location in free flow condition (V_{HF} km/h),

x_1, x_2 = vectors of independent variables representing street features,

β_0 = estimable parameter (constants),

ε = disturbance terms, and

β_1, β_2 = estimable parameters (Coefficients of independent variables to be calculated)

To obtain the best fit model, all the assumptions for multiple linear regressions have been checked step by step. First, scatter plots and a simple regression method was applied to ascertain the possible relationships between the independent variables and each dependent variable and then regression model was developed by using the possible combinations of the selected independent variables. Second, multicollinearity test was performed by checking the variance inflation factor (VIF<5.0). Extreme data were eliminated from the model on the basis of the multicollinearity test result. Finally, all other assumptions of linear regression such as homoscedasticity, normally distributed errors and error independence were also tested. After checking all assumptions, the independent variables having a significant level of 95% were inserted in the final speed models. In this research, categorical forms were considered for every independent variable.

3.5.3 Dependent variable

Speed data measured at the location of hump was considered as dependent variables in this part of the study. For better understanding about the speed mechanism in residential streets the road features integrated as independent variables in the speed models were arranged in two forms such as “Basic Factors” and “Sub Factors”. Table 3.2 represents the descriptive statistics of hump speed for each study location and Table 3.3 presents the descriptive statistics of the dependent variables for regression model respectively.

Table 3.2 Summary of descriptive statistics of hump speed (km/h) for each location

Site No	Sample Number	Mean Speed	Standard Deviation	Maximum Speed	Minimum Speed
01	25	10.586	2.619321	15.65	8.25
02	26	10.99167	4.20044	17.91	8.13
03	25	24.892	3.772357	29.7	18.44
04	28	24.17778	4.847861	35.26	16.12
05	29	24.70263	6.611794	35.65	12.25
06	29	30.30211	7.335296	44.02	16.24
07	28	22.05611	8.262771	42.3	11.01
08	26	14.18875	2.499584	18.05	8.02
09	27	17.65353	5.908792	34.85	11.03
10	26	13.04813	2.060386	16.46	10.08
11	27	36.83294	4.163802	43.6	31.75
12	28	39.12222	7.10363	50.76	26.98
13	26	33.07813	4.705556	40.93	23.45
14	29	42.97316	5.034297	55.38	37.9
15	20	34.1785	3.494375	41.47	28.31
16	25	39.444	5.319119	47.83	28.73
17	28	39.41611	5.540706	53.7	30.8
18	27	23.29	9.733701	36.88	10.76
19	26	15.81938	2.18035	18.82	11.04
20	28	15.68944	3.840126	21.01	8.21

Table 3.3 Descriptive statistics of the dependent variables

Variable Code	Sample Size	Mean	SD	Max	Min
V_{HF}	333	26.46	11.38	55.38	8.02

3.5.4 Operating speed models

(a) Considering road geometric features (basic factors)

The road features that are naturally exist in almost all residential streets such as road length, lane width, number of lane, road width, presence of sidewalk, pedestrian crossing or intersection etc. are referred as “Basic factors” in this study. Table 3.4 provides the operating speed models considering the basic factors as independent variables with the 95% level of significance.

Table 3.4 Operating speed models for free flow conditions (basic factors)

Variable	Dummy Category	Estimated Coefficient	t-ratio	sig
Constant		2.437	9.041	0.000
Length-200	1= 100.01 m to 200 m; 0 = otherwise	0.503	8.302	0.000
Sinusoidal Hump	1 = Sinusoidal, 0 = otherwise	-1.147	-6.889	0.000
Trapezoidal Hump 2	1 = Trapezoidal hump (top length - 14 to 20m), 0 = otherwise	0.561	8.178	0.000
Presence of Intersection	1 = yes, 0 = otherwise	0.140	2.059	0.040
Presence of Parking	1 = yes, 0 = otherwise	0.358	5.818	0.000
Presence of Crossing	1 = yes, 0 = otherwise	0.151	2.836	0.005

Note: Dependent Variable: Logarithm of Speed at Hump Ln V_{HF} (km/h)

Number of observations = 333; Adjusted R^2 = 0.453; Significance level = 95%

(b) Analysis of variance for the speed model based on basic factor

Table 3.5 showed the result of the analysis of variance (ANOVA) of the regression model developed based on basic factors. As the p-value is less than 0.05 in the given table, it can be said that the developed regression model for basic factors is significant.

Table 3.5 Analysis of variance for speed model based on basic factor

Model		Sum of Squares	df	Mean Square	F	p-value
1	Regression	34.852	8	4.357	34.804	0.000
	Residual	40.557	324	0.125		
	Total	75.409	332			

(c) Considering road geometric features (sub factors)

In some of the study locations, the number of T- intersection, crossing and parking was found more than one along the entire road section and these are located at a certain distance far from the device i.e. at 20m distance from hump or 40m distance from the device or so on. Depending on the distance between the basic factors and hump in each study location; the basic factors are further divided into sub factors. Table 3.6 shows the description of sub factors in detail.

Table 3.6 Description of sub factors

Basic Factor	Sub Factor	Description
Presence of T Intersection	Inter_Hump_Bef_20 Inter_Hump_Bef_40 Inter_Hump_Bef_60 Inter_Hump_Bef_80 Inter_Hump_Bef_100	Distance between T intersection (present before hump) and Hump location is 0-20m, 21-40m, 41-60m, 61-80m and 81-100m respectively
	Inter_Hump_aft_20 Inter_Hump_ aft_40 Inter_Hump_aft_60 Inter_Hump_ aft_80 Inter_Hump_aft_100	Distance between T intersection (present after hump) and Hump location is 0-20m, 21-40m, 41-60m, 61-80m and 81-100m respectively
	Inter_Hump_ both_20 Inter_Hump_ both_40	Distance between T intersection (present at both side of hump) and Hump location is 0-20m, 21-40m, respectively
Presence of Crossing	Cross_Hump_20 Cross_Hump_40	Distance between crossing and Hump location is 0-20m, 21-40m, respectively
	Cross at Hump	Crossing present at hump
Presence of Parking	Park_Hump_20 Park_Hump_40 Park_Hump_60 Park_Hump_80	Distance between parking and Hump location is 0-20m, 21-40m, 41-60m and 61-80m respectively
Presence of Pedestrian Entry	Entry_Hump_20 Entry _Hump_40 Entry _Hump_60	Distance between entry point and Hump location is 0-20m, 21-40m and 41-60m respectively
	Entry at Hump	Entry present at hump

Table 3.7 provides the operating speed models considering the sub factors as independent variables with the 95% level of significance.

Table 3.7 Operating speed models for free flow condition (sub factors)

Variable	Dummy Category	Estimated Coefficient	t-ratio	sig
Constant		2.971	51.416	0.000
Inter_Hump_Bef-20	1 = Distance between T before hump and Hump is 0-20m, 0 = otherwise	-0.818	-10.550	0.000
Inter_Hump_Bef-40	1 = Distance between T before hump and Hump is 21-40m, 0 = otherwise	-0.641	-6.631	0.000
Inter_Hump_Bef-60	1 = Distance between T before hump and Hump is 41-60m, 0 = otherwise	0.797	9.747	0.000
Inter_Hump_Bef-80	1 = Distance between T before hump and Hump is 61-80m, 0 = otherwise	1.271	11.953	0.000
Inter_Hump_Aft-20	1 = Distance between T after hump and Hump is 0-20m, 0 = otherwise	-0.570	-5.801	0.000
Inter_Hump_Aft-40	1 = Distance between T after hump and Hump is 21-40m, 0 = otherwise	0.653	9.100	0.000
Inter_Hump_Aft-60	1 = Distance between T after hump and Hump is 41-60m, 0 = otherwise	1.194	10.569	0.000
Inter_Hump_Both_40	1 = Distance between T both side of hump and Hump is 21-40m, 0 = otherwise)	0.234	2.414	0.016
Park_Hump_20	1 = Distance between parking and Hump is 0-20m, 0 = otherwise	0.181	2.735	0.007
Park_Hump_40	1 = Distance between parking and Hump is 21-40m, 0 = otherwise	-0.193	-3.460	0.001
Park_Hump_80	1 = Distance between parking and Hump is 61-80m, 0 = otherwise	0.697	8.443	0.000
Cross_Hump_20	1 = Distance between crossing and Hump is 0-20m, 0 = otherwise	0.394	5.509	0.000

Note: Dependent Variable: Logarithm of Speed at Hump Ln V_{HF} (km/h); Number of observations = 333; Adjusted R^2 = 0.691; Significance level = 95%

(d) Analysis of variance for the speed model based on sub factor

Table 3.8 showed the result of the analysis of variance (ANOVA) of the regression model developed based on sub factors. As the p-value is less than 0.05 in the given table, it can be said that the developed regression model for sub factors is also significant.

Table 3.8 Analysis of variance for speed model based on basic factor

Model		Sum of Squares	df	Mean Square	F	p-value
1	Regression	49.870	14	3.562	39.545	0.000
	Residual	28.645	318	.090		
	Total	78.515	332			

3.6 Results and Discussions

The developed models in Table 3.3 and Table 3.6 indicate that on neighborhood streets with 30 km/h speed limit where speed humps are present, the vehicle speeds are associated with various geometric road features. Brief interpretations of the results for the developed models are discussed in this section.

3.6.1 Regression model based on basic factors

According to the result of regression analysis, it has been found that the hump speed (V_{HF} km/h) is positively associated with the length of road. In this study, the variable Length-200 means that the road length is more than 100 m. The positive effect of this variable indicated that vehicle speed increases with the increasing length of road as because the drivers got additional spaces for acceleration due to longer road section (Dinh *et al.*, 2013). The hump speed increased by 0.503σ (5.75 km/h), for every one meter increase of length.

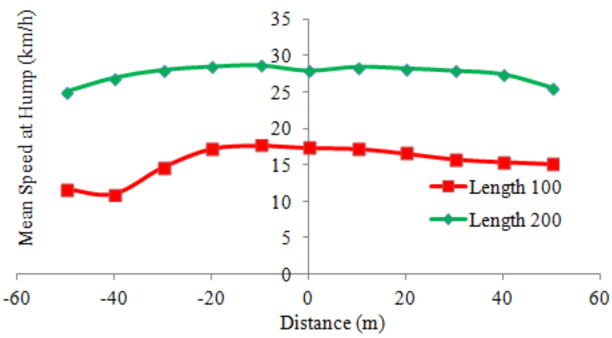
The developed model clearly showed that speed at hump location (V_{HF} km/h) is strongly influenced by the shape of hump. The hump speed reduced by sinusoidal hump (13.11 km/h) and increased by trapezoidal hump (6.41 km/h). It is the evident that sinusoidal hump is more effective in reducing vehicle speed than trapezoidal hump; as the sinusoidal hump has shorter length and steeper slope of the ramp compared to trapezoidal hump, which force drivers to slow down their speed. This negative effect of sinusoidal hump is consistent with the findings of (Kamada et al., 2015).

Due to the presence of T intersections; the hump speed increased by 0.140σ or 1.6 km/h. According to the findings of Dinh and Kubota (2013); compared to 4-leg intersection, T intersection or 3-leg intersection encourage drivers to speed up.

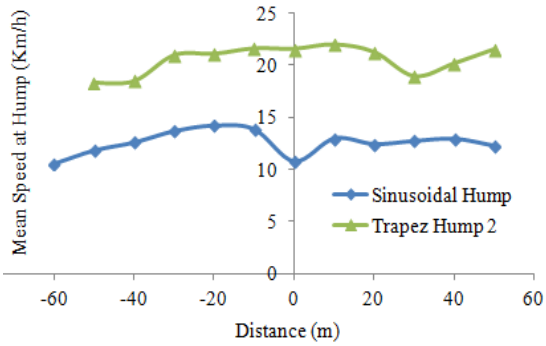
The regression result showed that, if any parking space is located within the road section, the speed at hump location (V_{HF} km/h) increased by 0.358σ or 4.1 km/h. The possible reason might be the condition of free flow. As this study measured speed data during free flow movement of target vehicle which means that there is no car moving on the study road except the target car. Therefore, the presence of parking slot has no direct effect on drivers speed choice.

Similarly, the hump speed also increased by 0.151σ or 1.72 km/h due to the presence of pedestrian crossing at the study location. As because of the same reason; the condition of free flow traffic. If there is no pedestrian activity along the road, the car speed might not be influenced by the existence of pedestrian crossing.

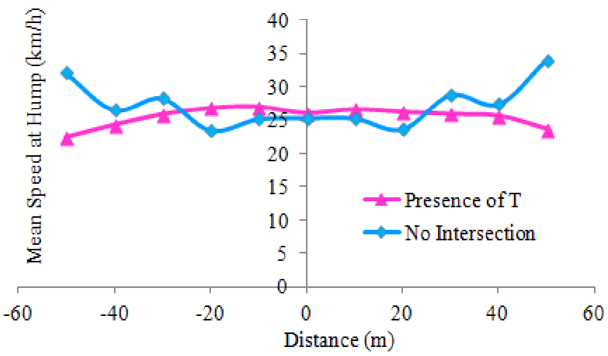
Figure 3.8 graphically represent the results of the developed regression model based on basic factors



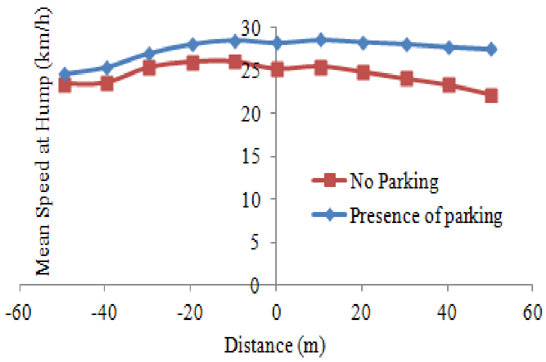
Length of Street Section



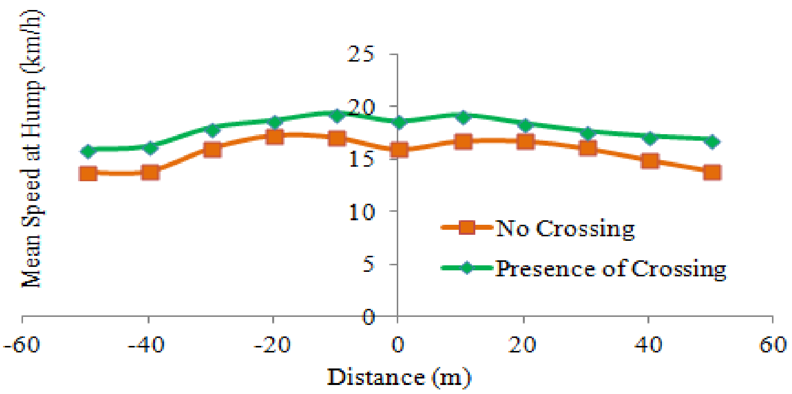
Shape of Hump



Presence of T Intersection



Presence of Parking



Presence of Pedestrian Crossing

Fig. 3.8 Variation of mean speed at hump location with selected street features based on regression model (considering basic factors)

3.6.2 Regression model based on sub factors

From the regression analysis, it can be seen that the vehicle speed at device location (V_{HF} km/h) started to decrease due to the presence of un-signalized T intersection within 20m to 40m distance before hump. Hump speed reduced by 0.818σ (9.3 km/h) and 0.641σ (7.3 km/h) if any T intersection present at 20m and 40m distance upstream of hump respectively. The negative effect of these influential factors in the present study is consistent with the findings of Tarris *et al*. (1996). The increasing density of T intersection along the road induces drivers to move slowly.

However, the presence of T intersection at a far distance before hump i.e. 60m or 80m acted reversely on hump speed (V_{HF} km/h). In that case hump speed increased by 0.797σ and 1.271σ if intersection present within 60m or 80m distance before hump.

The probable cause might be the driving priority of the through traffic. According to the research hypothesis, the through traffic should go first and the other vehicles should wait before making turn.

Furthermore, the developed model revealed that hump speed decreased due to the presence of T intersection at 20m distance after hump. Afterwards, V_{HF} km/h started to increase from the 40m distance downstream of hump. It indicated that hump is effective in marinating a lower speed until 20m distance downstream of hump.

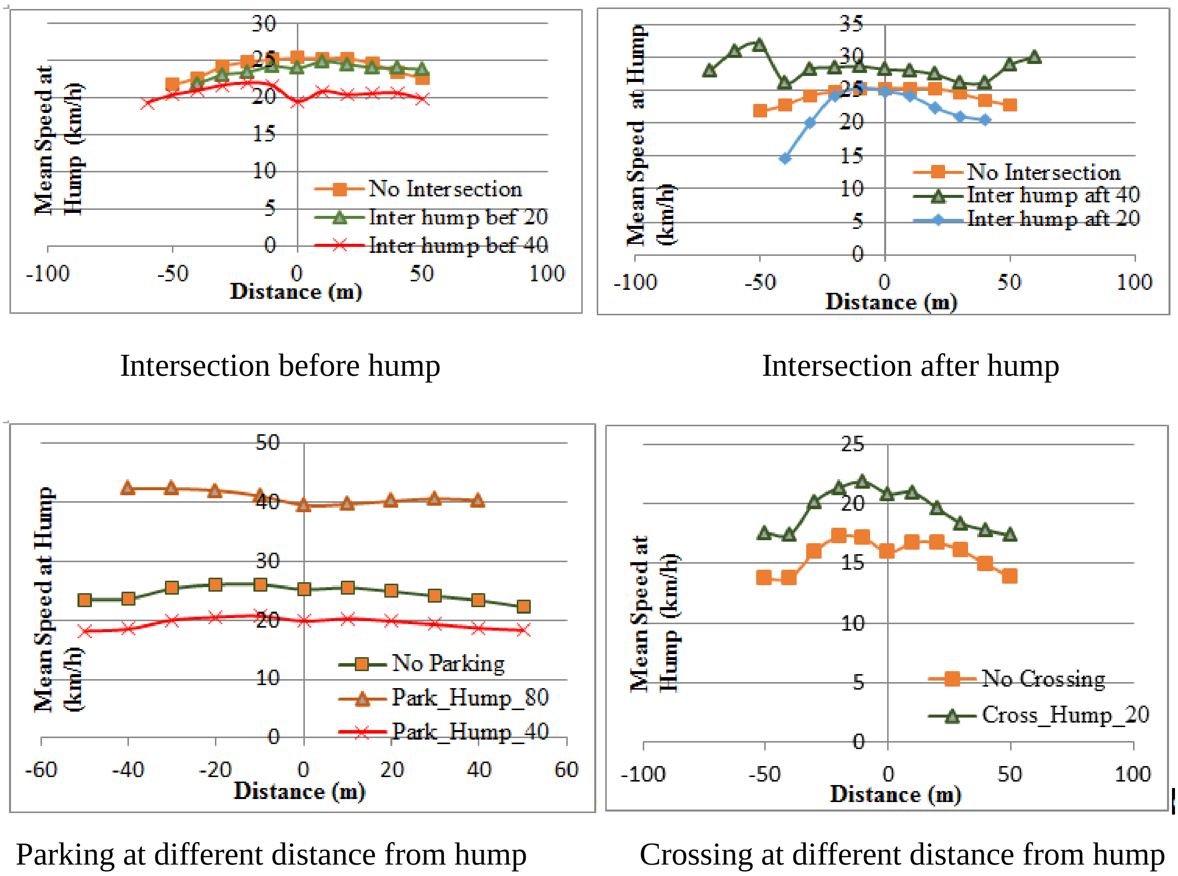
On the other hand, if T intersection present at both side of humps in one road it will increase the device speed. The possible explanation is that, driver will reduce their speed before 40m distance of hump and then maintain the lower speed until 40m distance after hump.

The variable named Park_Hump_20m means parking present at a distance of 20m vicinity of hump. From the analysis it has been found that hump speed is positively associated with the existence of parking nearby the device. The probable cause of this positive effect of parking might be the free flow movement of target vehicle along the entire road section. V_{HF} km/h increased by 0.181σ or 2.06 km/h if parking present at 20m distance on both side of hump in one street.

V_{HF} km/h started to decrease by 0.193σ or 2.21 km/h if parking present within 40m distance on both side of hump and increased by 0.697σ due to the presence of parking within 80m distance.

Furthermore, hump speed is positively associated with the presence of crossing nearby the device location i.e. 20m distance from hump. The positive effect of this influential factor is consistent with the findings of Johansson, C. (2011). Hump speed increased by 0.394σ or 4.5 km/h if crossing is present at a distance of 20m vicinity of hump.

Figure 3.9 graphically represent the results of the developed regression model based on sub factors



Intersection before hump — Intersection after hump

Parking at different distance from hump — Crossing at different distance from hump

Fig. 3.9 Variation of mean speed at hump location with selected street features based on regression model (considering sub factors)

3.7 Conclusions

This part of the current dissertation investigated hump speeds on 20 different residential streets in Japan having 30 km/h speed limit and containing several geometric road features. In this study it has found that about 38% drivers driving above the posted speed limit i.e. driving at a speed of 40 km/h or sometimes even more. To make a residential neighborhood inherently calmer it is needed to examine the speed on that area in detail even after the installation of traffic calming device such as speed hump. Therefore, this research is designed to identify the external factors affecting the effectiveness of speed hump especially in free flow condition.

For the study purpose two operating speed models were developed based on road characteristics by using multiple linear regression analysis. The regression results based on basic factors revealed that study street length, presence of intersection, parking and crossing are associated positively with hump speed whereas shape of hump is associated negatively. Furthermore, the model developed based on sub factors concluded that installing hump at a distance of 20m vicinity of any unsignalized T intersection can reduce vehicle speed more effectively.

The research outcome may enhance the rational guideline for use of humps to ascertain traffic safety. The findings from this study provide helpful information for urban planners, policy makers and other people who want to introduce speed hump on urban residential areas having 30 km/h speed limit or to address speeding issues in similar conditions. Continuing research is suggested to cultivate more enduring benefits.

However, this study is confined to investigate the effect of speed at hump location only. Further research is recommended to identify the factors affecting the speed at the entire section of road not only the location of device. As to maintain a lower speed along the road section it is important to evaluate the speed of that road in detail.

CHAPTER 4

Speed Reduction Characteristics in the Upstream of Speed Hump

4.1 Introduction

According to the result described in chapter 3, it was found that different road geometric factors e.g., study street length, shape of hump, presence of T intersection, parking, crossing, etc. affect the vehicle speed reduction at the location of hump (Rahman *et al.*, 2017).

However, for a safer and more livable residential neighborhood, not only the hump location should be a target, but also it is important to ensure the safe speed throughout the road section. Definitely, speed hump can reduce vehicle speed at hump location and after hump location (downstream). According to Smith *et al.* (2002), speed hump can reduce mean vehicle speed and 85th percentile vehicle speed effectively at the location of the hump and in the downstream of the hump, but not in the upstream of the hump. Another study analyzed the motorcyclist’s riding behavior on the hump and found that at the starting point the mean speed was increased and then reached to peak at a 70m distance upstream from the hump and again started to decrease from 60m upstream of the device (Yuen *et al.*, 2017). The probable cause might be higher uncertainties associated with speed reduction characteristics at the upstream of the device. For a better understanding of the speed reduction mechanism due to humps, a study on the upstream side is particularly important. There might be several external factors affecting the upstream speed reduction.

Existing literature showed that the hump speed and speed at the upstream side of the hump are affected by different roadway and roadside characteristics. According to Wang *et al.* (2009), car speeds were changed due to the presence of bump in front of an intersection and the speeds started to decrease at 30 m upstream of the speed bump. Moreover, Pau (2002) reported that due to the presence of pedestrian crosswalk near the bump, vehicle speeds were reduced at 20 m upstream of the bump. Similarly, it has also found that longer study street length resulted in higher speed at the location of the hump (Rahman *et al.*, 2017).

Other than geometric factors, non-geometric factors may also have a significant influence on speed reduction, such as street with many pedestrians. Driver’s on-street speed choice somewhat also depends on the existence of vulnerable road users along the road section. According to Dinh and Kubota (2013), more than 50% drivers in neighborhood streets would speed up in a wider road and if the road is free from pedestrians/cyclists; on the other hand, maximum drivers would slow down while driving on a road without sidewalk with vulnerable road users along the roadside.

Previous research has been limited to consider the effect of road geometric features on speed. Therefore, it is needed to explore the effect of non-geometric factors along with geometric features on speed in the presence of a single speed hump so that the speed reduction mechanism in the residential streets can be understand well and best possible position of hump can be identified which have significant influence for vehicle speed reduction along the entire length of the road.

4.2 Study Objective

The objective of this part of the research is to investigate the external geometric and non-geometric factors associated with the speed reduction in the upstream of humps. Among the different shapes of sinusoidal humps; two types named “Bow Shape” and “Top-Flat” are commonly found in the urban residential streets in Japan (Japan Society of Traffic Engineers, 2017). Therefore, these two types of humps have been particularly focused on this part. A total of 500 car speed data with a study length of 120m in both the upstream and downstream side were collected from 7 different residential streets in Japan. However, this chapter is only investigated the characteristics of speed reduction in the upstream side of device where a single hump installed along the road. Speed models at a distance of 10m interval in the upstream side have been developed to examine the influencing factors by employing multiple linear regression analysis. According to Yuen *et al.* (2017), the vehicle speed is negatively associated with the distance from the hump. Therefore, the speed at every 10m distance has been taken under consideration to check the actual condition of speed along the entire road.

4.3 Methodology

The methodology of this chapter is shown in the following framework

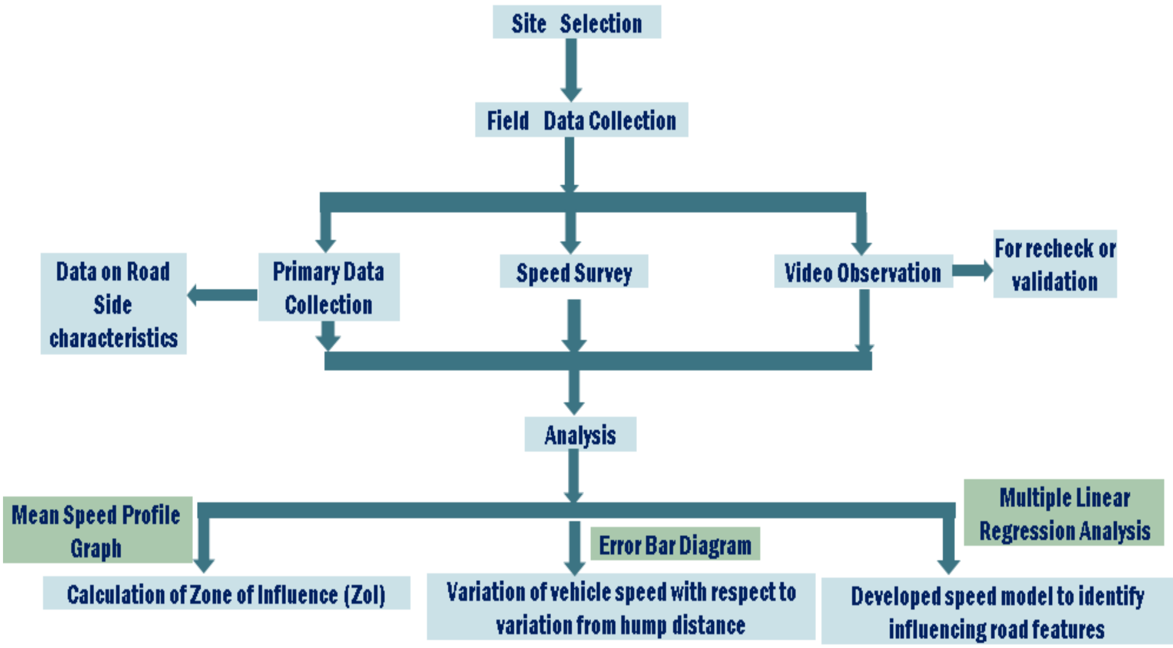
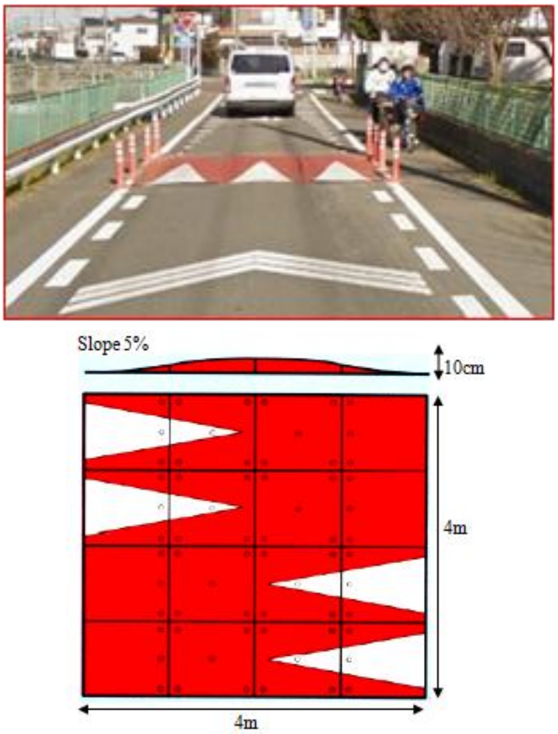


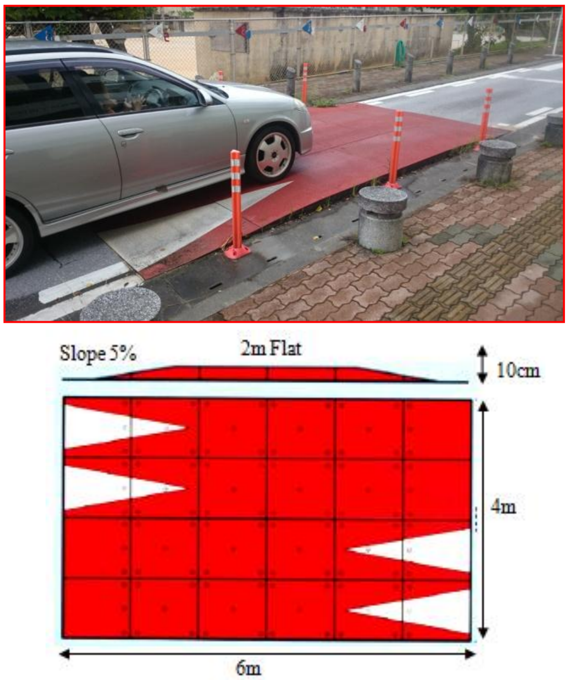
Fig.4.1 Conceptual framework for analysing speed reduction characteristics in the upstream side of hump

4.4 Data Collection

Data collection procedure is same as discussed in previous chapter (refer to section 3.4 in chapter 3). Continuous speed data were collected for individual vehicles by using STALKER ATS radar gun on 7 different locations in Japan. Among these, 4 (Asaka, Kita-Ageo, Miyoshi and Tsurugashima) were located in Saitama Prefecture, 1 (Okurayama) was in Kanagawa Prefecture and another 2 (Urasoe and Nakanishi) were in Okinawa Prefecture. Two types of the hump (bow shape, and top-flat) were investigated in this part. Figure 4.2 shows the shape of the humps.



(a) Bow Shape Hump



(b) Top-Flat Hump

Fig. 4.2 A typical picture of two shapes of the hump in the study area

4.4.1 Selected site characteristics

Among the four locations of Saitama Prefecture, three locations have residential areas along one side of the road while the other sides have different landscape settings, like embankment or agricultural field, etc. Only one location of Saitama has residential neighborhoods along both sides of the selected street. In the case of Okinawa and Kanagawa prefecture, all the selected locations are busy with pedestrian activities along the road because of the presence of the elementary school and railway station very close to the study roads. Furthermore, the selected street sections have various types of geometric features such as availability of sidewalk, street marking, the presence of T intersection or parking or crossing, etc. The total length of the selected roads varied between 180m to 300m where the hump is located in the middle position or close to the middle portion of the total study length. General descriptions of the selected road sections are summarized in Table 4.1.

Table 4.1 Summary of selected street section characteristics

Characteristics	Measured value
Length of Street Section (m)	180 to 313; mean: 233.37
Traffic Direction	Two-way: 6 Sites; One-way: 1 Site
Roadway Width (m)	3.95 to 8.95; mean: 6.11
Carriageway Width (m)	2.75 to 6.63; mean: 4.27
No of Lanes	1 to 2; mean: 1.14
Left Safety Strip Width (m)[a]	0.5 to 1.16; mean: 0.88
Right Safety Strip Width (m)[b]	0.5 to 1.16; mean: 0.95
Presence of Sidewalk	No: 5 sites; Both side: 2 sites
Street Marking	No: 1 site; Edge Marking only: 6 sites
Presence of Pedestrian Entry Point [c] (Before hump)	Yes: 4 sites, No: 3 sites
Street with many Pedestrian[s]	Yes: 3 sites; No: 4 sites
Shape of Hump	Bow Shape: 4 sites; Top-Flat: 3 sites
No of T Intersection (Before hump)	Yes: 5 sites; No: 2 sites
Presence of T intersection (Before hump) [e]	0-20m: 1 site; 21-40m: 3 sites; 41-60m: 2 sites; 61-80m: 1 site; 81-100m: 1 site; 101-120m: 1 site
No of Parking (Before hump)	Yes: 6 sites; No: 1 site
Presence of Parking (Before hump)[f]	0-40m: 2 sites; 41-80m: 4 sites; 81-120m: 4 sites
Presence of Crossing (Before hump)[g]	0-60m: 1 site; 61-120m: 0 site

Notes: [a]Left Safety Strip Width (m) - Distance between the edges of a study lane to the curb on the left side of the target direction. [b]Right Safety Strip Width (m) - Distance between the edges of a study lane to the curb on the right side of target direction. [c]Presence of Pedestrian Entry Point - It is the point (such as any park or building, etc.) from where pedestrian directly comes on road and possibility to cross the road; either horizontal pedestrian crossing is available on that road or not. [d]Street with many Pedestrians – It is the road without sidewalk with vulnerable road users along the roadside. [e]Presence of T intersection (before hump) – Presence of T intersection at 20m distance interval from hump (in the upstream). [f]Presence of Parking (Before hump) - Presence of Parking at 40m distance interval from hump (in the upstream). [g]Presence of Crossing (Before hump) - Presence of Crossing at 60m distance interval from hump (in the upstream).

4.4.2 Speed data collection

Speed data were collected following the same procedure as mentioned in chapter 3 section 3.4.3. However, for this part of the research at least 40 profile speeds were collected for each study sites. After filtering the interrupted data through video observation, a total of 487 individual speed profiles in free flow conditions for seven locations remained for further analysis.

4.5 Data Analysis

4.5.1 Calculation of zone of influence for the study locations

The zone of influence (ZoI) is the area over which vehicle speed reducing effect occurs under the application of traffic calming device (Daniel *et al.*, 2011). The sum of the influence zones either side of the device is called the total zone of influence for an isolated traffic calming device. This definition was used to determine ZoI of the selected study sections. An illustration of the vehicle means speed profile along a traffic-calmed street under the current study is shown in Figure 4.3 as an example.

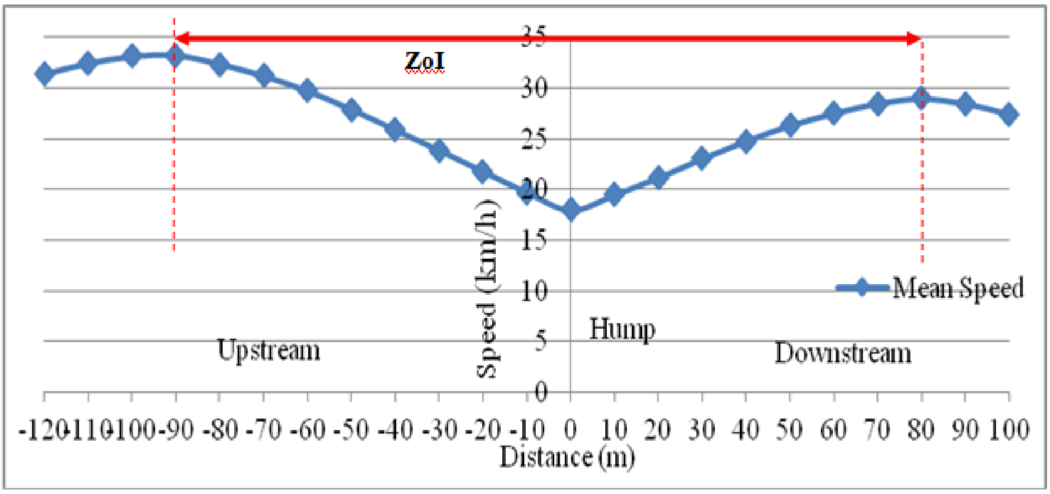


Fig. 4.3 Mean speed profile showing ZoI of one study location

From Figure 4.3, it can be seen that the mean speed starts to reduce at the beginning point of ZoI in the upstream and gets back to the initial constant speed at the ending of ZoI, which demonstrates the diminished effect of hump beyond the ZoI. ZoI for two types of humps in the seven different locations is summarized in Table 4.2

Table 4.2 Summary of the zone of influence of different sites

Study Sites	Name of Prefecture	Types of Hump	ZoI (m)	Maximum upstream length (m)	Maximum downstream length (m)
Asaka	Saitama	Bow Shape	-60 to +70	120	110
Kita-Ageo	Saitama	Bow Shape	-60 to +50	120	80
Miyoshi	Saitama	Bow Shape	-60 to +50	120	80
Tsurugashima	Saitama	Bow Shape	-60 to +50	120	80
Makiminato	Okinawa	Top-Flat	-80 to +70	120	120
Nakanishi	Okinawa	Top-Flat	-60 to +60	80	80
Yokohama	Kanagawa	Top-Flat	-70 to +70	120	120

Note: Negative (-) sign indicates the distance from the hump in the upstream and a positive (+) sign indicates the distance from the hump in the downstream.

From Table 4.2, it has been found that other than Nakanishi, all other location has a maximum upstream length of about 120m and the influencing area of hump ranges between 80m upstream to 70m downstream in case of Top-Flat hump and 60m upstream to 70m downstream in case of Bow shape hump, which is consistent with the findings of Yuen *et al.* (2017). Top-Flat hump has the longest and Bow shape of hump has the shortest zone of influence.

4.5.2 Variation of vehicle speed with respect to the variation from hump distance

The variation of car speed in each study location is shown in Table 4.3. The variation is measured by calculating the standard deviation of vehicle speed at every 10m distance interval from hump both in the upstream and downstream side. The interval of 10m was selected purposefully in order to avoid unwanted interference of traffic flow (due to the presence of intersection or other road features). According to Zainuddin *et al*. (2014), interference is prominent at a distance of 15m or more.

From the table, it is evident that as the distance from hump location increases, the variation in speed becomes larger. Nevertheless, outside the ZoI, the variation in the upstream speed at a certain amount is larger than that of the downstream speed. This distinct behavior influenced the authors to focus on the investigation of the speed reduction mechanism, particularly in the upstream side.

Table 4.3 Variation of vehicle speed with respect to variation from hump distance

Distance from Hump	Standard Deviation of Car Speed at Study Locations						
	Asaka	Kita-Ageo	Miyoshi	Tsurugashima	Maki-minato	Nakanishi	Yokohama
-120	7.16	5.72	7.16	5.73	5.76	-	5.20
-110	7.09	5.58	6.83	5.65	5.45	-	5.31
-100	6.85	5.50	6.43	5.60	5.12	-	5.92
-90	6.59	5.22	6.18	5.44	4.72	-	5.86
-80	6.49	5.18	5.73	5.21	4.36	4.29	5.78
-70	6.37	4.97	5.36	4.99	4.46	4.37	5.33
-60	6.28	4.86	4.93	4.76	4.35	4.39	5.36
-50	6.07	4.59	4.60	4.50	4.25	4.67	5.01
-40	6.14	4.46	4.60	4.46	3.94	4.74	5.90
-30	6.24	4.47	4.65	4.49	3.82	4.87	5.17
-20	6.44	4.59	4.50	4.52	3.63	4.99	5.83
-10	6.81	4.87	3.90	4.67	3.54	4.92	5.42
0	**6.08**	**4.17**	**3.87**	**4.03**	**3.50**	**4.81**	**4.95**
+10	6.68	4.09	2.99	4.25	3.88	4.21	4.96
+20	6.13	3.00	2.55	3.39	3.93	4.22	5.43
+30	5.58	2.57	2.73	3.17	4.22	4.35	5.53
+40	5.15	2.70	2.56	3.20	4.63	4.64	5.30
+50	5.08	2.50	1.43	3.64	4.67	4.41	5.19
+60	5.10	2.61	1.40	3.58	5.04	4.23	5.40
+70	5.18	2.84	2.33	3.13	4.60	4.15	5.58
+80	5.22	3.01	2.46	2.96	2.76	4.11	5.75
+90	5.39	-	-	-	2.90	-	5.43
+100	5.60	-	-	-	3.06	-	5.01
+110	5.62	-	-	-	3.95	-	4.20
+120	5.70	-	-	-	4.07	-	3.61

Note: Negative (-) sign indicates the distance from the hump in the upstream and a positive (+) sign indicates the distance from the hump in the downstream. Green color indicates the location at the hump.

4.5.3 Analysis of variance of vehicle speed based on study location

The result of analysis of variance (ANOVA) of car speed in each location is shown in Table 4.4 and 4.5. From these tables, it can be seen that the variation between groups is enough big compared to variation within groups. This indicated that there is a significant difference between the car speeds of each study locations.

Table 4.4 Analysis of variance of car speed at a distance of 60m to 120m upstream of hump

Location	Sample Size	Distance in the upstream of the hump (m)						
		120m	110m	100m	90m	80m	70m	60m
Asaka	73	31.39[a*] (7.16)[b*]	32.44 (7.09)	33.12 (6.84)	33.23 (6.59)	32.35 (6.49)	31.18 (6.36)	29.72 (6.28)
Kita-Ageo	97	39.3 (5.7)	39.52 (5.57)	39.46 (5.49)	38.90 (5.21)	37.85 (5.17)	36.56 (4.96)	34.85 (4.86)
Miyoshi	89	39.74 (7.16)	39.41 (6.82)	39.05 (6.42)	38.56 (6.18)	37.82 (5.72)	36.63 (5.36)	35.02 (4.93)
Tsurugashima	91	35.80 (5.72)	35.69 (5.65)	35.27 (5.59)	34.57 (5.44)	33.54 (5.20)	32.32 (4.99)	30.96 (4.75)
Makiminato	40	23.40 (5.76)	24.59 (5.45)	25.71 (5.11)	26.47 (4.72)	27.10 (4.35)	27.62 (4.45)	27.84 (4.34)
Yokohama	50	19.25 (4.20)	19.19 (4.30)	19.96 (4.42)	20.79 (4.85)	19.35 (4.77)	18.03 (5.32)	20.35 (5.35)
Nakanishi	47	-	-	-		20.18 (4.28)	20.61 (4.36)	20.03 (4.39)
p-value		***	***	***	***	***	***	***

Note: a* - Mean speed of all vehicles in a particular location at a certain distance from the hump

b* - Standard deviation of vehicle speed

* p<0.05, ** p<0.01, *** p<0.0001

Table 4.5 Analysis of variance of car speed at a distance of 0m to 50m upstream of hump

Location	Sample Size	Distance in the upstream of the hump (m)					
		50m	40m	30m	20m	10m	Hump speed
Asaka	73	27.90[a*] (6.06)[b*]	25.91 (6.13)	23.88 (6.23)	21.80 (6.43)	19.74 (6.81)	18.00 (7.05)
Kita-Ageo	97	32.75 (4.58)	30.08 (4.45)	26.78 (4.47)	23.25 (4.58)	19.69 (4.87)	16.66 (5.16)
Miyoshi	89	33.12 (4.60)	30.75 (4.60)	27.57 (4.64)	23.35 (4.50)	18.46 (3.89)	15.03 (3.86)
Tsurugashima	91	29.21 (4.50)	26.93 (4.45)	24.28 (4.49)	21.28 (4.51)	18.24 (4.66)	15.66 (5.02)
Makiminato	40	27.73 (4.24)	27.18 (3.94)	25.87 (3.82)	23.97 (3.63)	18.82 (4.74)	14.45 (4.50)
Yokohama	50	21.58 (5.01)	22.68 (4.90)	23.50 (5.17)	23.14 (4.82)	20.69 (4.42)	17.72 (5.44)
Nakanishi	47	23.36 (3.87)	24.74 (4.14)	24.52 (4.56)	23.09 (4.99)	20.97 (4.92)	19.62 (5.01)
p-value		***	***	***	*	**	***

Note: a* - Mean speed of all vehicles in a particular location at a certain distance from the hump

b* - Standard deviation of vehicle speed

* p<0.05, ** p<0.01, *** p<0.0001

4.6 Model Development

For a better understanding of the characteristics of speed along the study segment, several speed models at a distance of 10 m interval in the upstream side from hump location were derived by using multiple linear regression analysis. The regression equation is as similar as shown in chapter 3 section 3.4.2; the equation no (2).

4.6.1 Dependent variable

The total study length of the selected seven locations varied from 180m to 313m. The maximum upstream and downstream length of six locations was 120m and 100m respectively, except Nakanishi, as mentioned earlier. For the six sites other than Nakanishi, the upstream length was divided into 12 sections at 10m interval, while for the Nakanishi, there were 8 sections. Speed data were measured at every section and considered as dependent variables. Table 4.6 represents the descriptive statistics of the dependent variables.

Table 4.6 Descriptive statistics of dependent variables

Variable "V_i"	N	Min. speed	Max. speed	Mean speed	SD
V_{10} (km/h)	487	9.01	43.54	19.36	5.03
V_{20} (km/h)	487	10.15	43.90	22.72	4.93
V_{30} (km/h)	487	9.80	44.77	25.40	5.05
V_{40} (km/h)	487	14.28	45.21	27.48	5.40
V_{50} (km/h)	487	9.20	45.76	28.97	6.13
V_{60} (km/h)	487	9.10	47.69	29.90	7.38
V_{70} (km/h)	487	9.13	50.00	30.80	8.24
V_{80} (km/h)	487	10.02	53.33	31.71	8.60
V_{90} (km/h)	440	9.18	54.29	33.81	8.13
V_{100} (km/h)	440	9.19	55.48	34.00	8.63
V_{110} (km/h)	440	9.90	56.92	33.87	9.08
V_{120} (km/h)	440	10.00	58.86	33.64	9.33

Note: "V_i" indicates the speed at a different upstream distance from the center of the hump at 10 m interval.

4.6.2 Operating speed models

Both geometric and non-geometric roadway and roadside characteristics has been considered as independent variables in this study e.g., length of study street section, number of lane, carriageway width, presence of sidewalk, shape of hump, presence of T intersection, presence of parking, presence of pedestrian entry point, street with many pedestrian, two-way traffic etc. Table 4.7 provides the finally selected models at a significance level of 95%.

Table 4.7 Operating speed models at 9 sections in the upstream

Variable	Estimated Coefficient	t-ratio	sig	Adj R^2	Sample Size
Dependent Variable: Logarithm of speed at 40m distance from hump (Ln V_{40}) (km/h)					
Constant	3.585	86.295	0.000***	0.248	487
Street Marking (1 = yes, 0 = other)	-0.193	-5.152	0.000***		
Top-Flat Hump (1 = Top-Flat, 0 = other)	-0.189	-8.567	0.000***		
Inter-Hump 0-20m (1 = T intersection at 0-20m distance from hump, 0 = other)	-0.164	-5.975	0.000***		
Inter-Hump 21-40m (1 = T intersection at 21-40m distance from hump, 0 = other)	-0.127	-4.386	0.000***		
Dependent Variable: Logarithm of speed at 50m distance from hump (Ln V_{50}) (km/h)					
Constant	3.746	92.299	0.000***	0.420	487
Sidewalk Presence (1 = Sidewalk on both side of road, 0 = no sidewalk)	0.075	3.389	0.001**		
Street Marking (1 = yes, 0 = other)	-0.267	-7.291	0.000***		
Top-Flat Hump (1 = Top-Flat, 0 = other)	-0.244	-11.005	0.000***		
Inter-Hump 21-40m (1 = T intersection at 21-40m distance from hump, 0 = other)	-0.203	-7.067	0.000***		
Park-Hump 0-40m (1 = Parking at 0-40m distance from hump,0 = other)	-0.172	-6.444	0.000***		

Note: * p<0.05, ** p<0.01, *** p<0.0001

Table 4.7 Operating speed models at 9 sections in the upstream

Variable	Estimated Coefficient	t-ratio	sig	Adj R^2	Sample Size
Dependent Variable: Logarithm of speed at 60m distance from hump (Ln V_{60}) (km/h)					
Constant	3.879	88.645	0.000***	0.560	487
Street Marking (1 = yes, 0 = other)	-0.339	-8.576	0.000***		
Top-Flat Hump (1 = Top-Flat, 0 = other)	-0.422	-17.653	0.000***		
Inter-Hump 21-40m (1= T intersection at 21-40m distance from hump, 0 = other)	-0.149	-4.810	0.000***		
Park-Hump 0-40m (1= Parking at 0-40m distance from hump, 0 = other)	-0.170	-5.907	0.000***		
Dependent Variable: Logarithm of speed at 70m distance from hump (Ln V_{70}) (km/h)					
Constant	4.325	52.856	0.000***	0.615	487
Two-way Traffic (1= Two way, 0 = other)	-0.203	-4.332	0.000***		
Street Marking (1 = yes, 0 = other)	-0.533	-11.094	0.000***		
Top-Flat Hump (1 = Top-Flat, 0 = other)	-0.741	-21.965	0.000***		
Park-Hump 41-80m (1 = Parking at 41-80m distance from hump, 0 = other)	-0.076	-3.050	0.002**		
Dependent Variable: Logarithm of speed at 80m distance from hump (Ln V_{80}) (km/h)					
Constant	4.172	52.605	0.000***	0.635	487
Two way Traffic (1= Two way, 0 = other)	-0.106	-2.332	0.020*		
Street Marking (1 = yes, 0 = other)	-0.442	-9.500	0.000***		
Top-Flat Hump (1 = Top-Flat, 0 = other)	-0.703	-21.510	0.000***		
Park-Hump 41-80m (1 = Parking at 41-80m distance from hump, 0 = other)	-0.077	-3.176	0.002**		
Dependent Variable: Logarithm of speed at 90m distance from hump (Ln V_{90}) (km/h)					
Constant	3.855	93.768	0.000***	0.532	440
Street Marking (1 = yes, 0 = other)	-0.255	-6.451	0.000***		
Street with many pedestrians (1 = yes, 0 = other)	-0.595	-20.717	0.000***		
Inter-Hump 61-80m (1 = T intersection at 61-80m distance from hump, 0 = other)	-0.069	-3.064	0.002**		

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.0001$

Table 4.7 Operating speed models at 9 sections in the upstream

Variable	Estimated Coefficient	t-ratio	sig	Adj R^2	Sample Size
Dependent Variable: Logarithm of speed at 100m distance from hump (Ln V_{100}) (km/h)					
Constant	3.866	91.394	0.000***	0.561	440
Street Marking (1 = yes, 0 = other)	-0.257	-6.338	0.000***		
Street with many pedestrian (1 = yes, 0 = other)	-0.640	-21.661	0.000***		
Inter-Hump 61-80m (1 = T intersection at 61-80m distance from hump, 0 = other)	-0.058	-2.469	0.014*		
Dependent Variable: Logarithm of speed at 110m distance from hump (Ln V_{110}) (km/h)					
Constant	3.218	80.418	0.000***	0.574	440
Road width> 6m (1 = Road width is more than or equal to 6.0 m, 0 = other)	0.634	17.979	0.000***		
Street Marking (1 = yes, 0 = other)	-0.247	-5.814	0.000***		
Dependent Variable: Logarithm of speed at 120m distance from hump (Ln V_{120}) (km/h)					
Constant	3.149	75.082	0.000***	0.557	440
Road width> 6m (1 = Road width is more than or equal to 6.0 m, 0 = other)	0.632	17.082	0.000***		
Street Marking (1 = yes, 0 = other)	-0.185	-4.161	0.000***		

Note: * p<0.05, ** p<0.01, *** p<0.0001

4.7 Results and Discussions

The developed models in Table 4.7 indicate that on neighborhood streets with 30 km/h speed limit where speed humps are present, the vehicle speeds are associated with various geometric and non-geometric road features. Brief interpretations of the results for each developed models are discussed in this section.

4.7.1 Regression Model at Different Distance from Hump in the Upstream

(i) 10m, 20m and 30m speed model

From the regression analysis, it can be seen that the vehicle speed at a 10m distance (V_{10} km/h) and 20m distance (V_{20} km/h) from hump are strongly influenced by the bow shape of the hump. Due to the short length and steeper slope of the ramp, bow shape hump generates more discomfort while negotiating over the hump and sharply reduces vehicle speed. However, the coefficient of correlation (R-Sq) values of the developed models is 0.036 and 0.041 respectively which are not significant. This is due to the fact that the variation in speed of all cars is small near hump location and hump is a dominant speed reducing factor within this 20m distance.

In the case of 30m speed model, the value of R-Sq (0.099) is also not significant, same as 10 m and 20 m speed model. Moreover, car speed at 30m distance from hump (V_{30} km/h) has changed due to the shape of hump and presence of T intersection in front of the hump. In this model, top-flat hump becomes significant instead of bow shape of hump.

(ii) 40m speed model

Speed at 40m distance from hump (V_{40} km/h) decreased by 0.193σ (1.04 km/h) for street marking presence on road and 0.189σ (1.02 km/h) for top-flat hump. Due to the effect of T intersection present at 20m and 40m distance from hump; V_{40} km/h reduced by 0.164σ (0.88 km/h) and 0.127σ (0.68 km/h) respectively. The negative effect of these influential factors in the present study is consistent with the findings of Rahman *et al*. (2017). The possible explanation of these findings can be elucidated, as the presence of T intersection very close to the hump location (i.e. within 40m distance before device location), which makes drivers more careful about speeding. It should be noted that from 40m speed model R-Sq becomes significant with a value of 0.248.

(iii) 50m and 60m speed model

From the model V_{50} km/h and V_{60} km/h, it can be seen that the presence of sidewalk and parking in the study road section become significant factor along with the top-flat hump, street marking and presence of T intersection. The availability of sidewalk on both sides of road resulted in higher speed (0.075σ or 0.46 km/h) at 50m distance from hump. The possible explanation of this positive effect is that; driver's perception regarding road safety somehow increased due to the presence of sidewalk on both side of the road which encourages them to speed up, thinking that the road will be free of vulnerable road users (Dinh and Kubota, 2013). On the other hand, drivers slow down their speed by 0.267σ (1.64 km/h) at 50m and 0.339σ (2.50 km/h) at 60m upstream of hump if street marking exists on study road.

Similarly, car speed at 50m and 60m upstream started to decrease due to the presence of un-signalized T intersection within 20m to 40m distance from hump. Vehicle speed reduces by 0.172σ (1.05 km/h) at 50m and 0.170σ (1.25 km/h) at 60m if parking is present within the 40m distance from the hump in the upstream. It indicates that, if any car suddenly comes out on road from any parking area, through traffic must have to reduce their speed and observe the following car's movement which encourages drivers to move slowly.

(iv) 70m and 80m speed model

Two-way traffic, street marking, top-flat hump and the presence of parking within 40m to 80m distance in the upstream are associated negatively with the vehicle speed at 70m (V_{70} km/h) and 80m (V_{80} km/h) distance before hump. V_{70} km/h decreases by 0.741σ (6.10 km/h) in case of top-flat hump, 0.533σ (4.4 km/h) due to existence of street marking on road and 0.076σ (0.63 km/h) by the presence of parking. This model further establishes that car speed reduction also depends on traffic direction. Two-way traffic is more pedestrian friendly than one-way street. A report by Pioneer Valley Planning Commission (2002) stated that, two-way traffic enhances drivers in reducing their speed. The developed model at 70m upstream shows that, vehicle speed started to decrease by 0.203σ (1.67 km/h) due to the effect of two-way traffic.

Similarly, for speed model at an 80m distance upstream of the hump (V_{80} km/h), 6.1 km/h speed and 3.8 km/h speed reduction caused by the effect of top-flat hump and street marking respectively. Furthermore, 0.66 km/h speed reduction occurs if parking present within 40m to 80m distance from device location.

(v) 90m and 100m speed model

The regression model developed at 90m (V_{90} km/h) and 100m (V_{100} km/h) distance from hump is the evidence that the effect of the hump is totally disappeared after ZoI. It indicates that hump is effective in reducing vehicle speed within the ZoI area and it becomes ineffective outside the ZoI area. Vehicle speed was influenced by other geometric features apart from hump e.g., street marking and presence of intersection along the study site. In this model, V_{90} km/h reduces by 0.255σ (2.1 km/h) if noticeable street marking exists on the road and 0.56 km/h by the presence of intersection within 60m to 80m distance upstream. Correspondingly, V_{100} km/h decreases by 2.22 km/h and 0.5 km/h due to the effect of road marking and intersection respectively. A non-geometric factor named "street with many pedestrian" had found a significant influence on the reduction of vehicle speed at 90m and 100m distance upstream of the hump. Drivers slow down their speed by 0.595σ (4.83 km/h) at 90m and 0.640σ (5.52 km/h) at 100m upstream if they found many vulnerable road users along the street section (Dinh and Kubota, 2013).

(vi) 110m and 120m speed model

The vehicle speed at 110m (V_{110} km/h) and 120m (V_{120} km/h) upstream of the hump are negatively associated with street marking. In case of visible road marking; speed decreases by 0.247σ (2.24 km/h) at 110m and 0.185σ (1.73 km/h) at 120m distance upstream. These models further establish that vehicle speed also depends on road width. If the road width is greater than 6.0m, speed increased by 5.8 km/h and 5.9 km/h at 110m and 120m distance from hump respectively. The positive effect of road width is consistent with the findings of Edquist *et al*. (2009).

4.8 Conclusions

Previous studies investigated mostly the speed reduction efficiencies of humps at the location of the hump. However, to make the residential neighborhood safe and secure, it is important to ensure safe operating speed throughout the entire road section, not only the hump location. This part of the research examines the speed reduction characteristics in the upstream side of a speed hump. A distinct behavior was observed in Table 4.3 which demonstrates that the variation in the upstream speed at a certain distance from hump is larger than that of the downstream speed. This finding influenced the author to focus particularly on the upstream side speed reduction mechanism. The speed characteristics at the upstream side of the hump are somewhat complicated due to uncertainties in speed reduction, which is associated with several influencing factors.

According to the study objective, 12 speed models have been developed at the selected 12 points in the upstream of hump by using multiple linear regression analysis. Various road geometric features e.g., road width, the shape of the hump, the presence of intersection and parking at a different distance from the hump, etc. found to be significant for vehicle speed reduction. Nonetheless, a novel non-geometric factor named "street with many pedestrians" was also introduced as a significant speed reducing factor. This study further revealed that the ZoI area of hump varies from location to location and for Top-Flat hump the range is from 80m upstream to 70m downstream whereas for Bow shape hump it is from 60m upstream to 70m downstream. Moreover, the regression analysis showed that within ZoI area hump is a significant speed reducing factor but outside the ZoI the effect of hump diminished.

The findings of the current study can help practitioners to understand comprehensively the speed reduction mechanism in the upstream side of a single hump. In addition, the desired value of speed along the upstream side of any road, where hump will be installed can also be predicted by using the developed models, making it easy to take a decision whether installing humps will be effective in reducing speed or not. However, this part of the research is confined to discuss the upstream speed reduction mechanism only; for better understanding about the speed reduction mechanism in residential neighborhood, it is important to analyze the speed along the entire length of road.

CHAPTER 5

Prediction Model and Optimum Placement of a Single Speed Hump

5.1 Introduction

A single speed hump is effective in reducing vehicle speed significantly in case of shorter road section. However, a single hump often insufficient to maintain a lower speed level along the road section where the section length is relatively long (i.e. 200m to 300m). In such cases, multiple humps with appropriate intervals are an alternate solution, yet expensive (Kojima *et al*., 2011). Therefore, it is important for the practitioners to find out the suitable position of a single hump instead of installing multiple humps; to keep up a low speed along the road section where the section length is relatively long.

Despite the effect of a single hump in speed reduction, it is still very rare in many Asian countries. In some Asian countries like Japan, India, Korea and Malaysia, humps were eventually found unsuccessful because of the inappropriate position and inconsistent dimension of humps (Bachok *et al*., 2016). The possible reason might be the different road geometry and the surrounding environment of Asian and American countries. For example, a study based on temporary speed humps was conducted on residential streets located in the Iowa City of United States found effective in reducing mean vehicle speed; where the road width was about 9m and a total of 27 households lived nearby the streets (Smith *et al*., 2002). The neighborhood streets of Iowa City had sidewalk on both side of road and a separate driveway to provide access to the adjacent buildings. Conversely, the residential roads in Japan provide direct access to the neighboring properties (Dinh and Kubota, 2013) and accommodate resident's daily life activities. Installing hump in such kind of streets also found effective in speed reduction but the reduction was found inconsistent. Probably, a variety of street features in the neighborhood streets of Japan (Dinh, 2013) affect the effectiveness of hump; as in Japan, most of the roads have a carriageway of one lane or two lanes with varying lane width from 6m to 9m. Some streets have sidewalks either on one side or both sides, while in a majority of streets, sidewalks are not available; pedestrians and cyclists have to share the roadways with motorized vehicles putting them at high risk for an accident. Therefore, for Asian countries further study is needed to establish a single hump as effective traffic calming measure in case of longer road section. The difference between the neighborhood street in Asian and American countries are shown in Figure 5.1.

Roosevelt Drive, IOWA City, USA　　　　Nakayama, Yokohama, Japan

Fig. 5 1 Neighborhood street pattern

[Source:

Roosevelt Drive-

https://www.google.com/maps/@41.3910215,95.0070979,3a,75y,24.27h,83.56t/data=!3m6!1e1!3m4!1sMtnY7TFTnx-FkLDhB1QlMg!2e0!7i13312!8i6656

Nakayama, Japan –

https://www.google.com/maps/@35.515098,139.5466273,3a,60y,305.59h,72.45t/data=!3m6!1e1!3m4!1s7wP4OTTCSWpJMTy_4ynTBA!2e0!7i16384!8i8192]

5.2 Study Objective

Based on the issues discussed earlier, the specific objectives of this part of the research are as follows:

- To develop a statistical relationship between the vehicle speed at different distance in upstream as well as downstream of hump and the roadway and roadside characteristics of residential areas where a single hump is present
- To validate the proposed developed models with respect to independent data sets collected from a new location having similar geometric configurations
- To demonstrate the application of the developed models for practical purposes.

5.3 Methodology

The conceptual framework for analyzing the speed data were shown in Figure 5.2

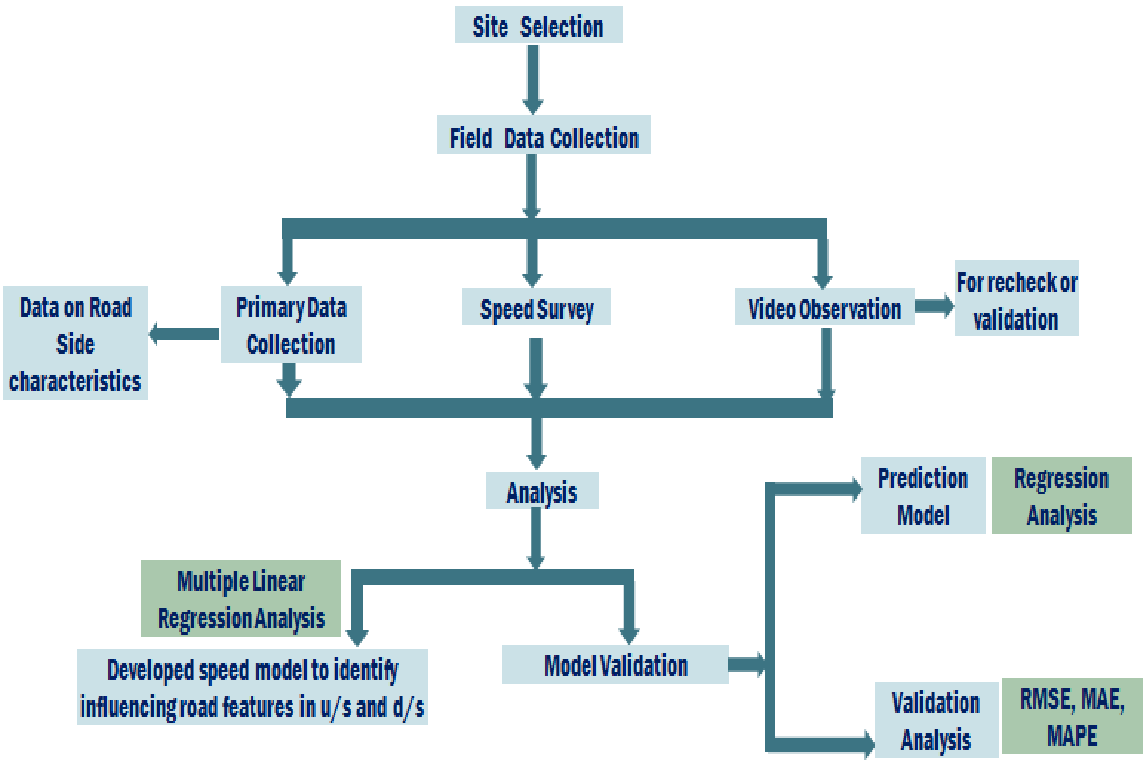


Fig. 5.2 Conceptual frameworks for analyzing speed along the entire road section

5.4 Data Collection

For this part of research, continuous speed data were collected from the same 7 locations as described in chapter 4 section 4.4 by using STALKER ATS radar gun. The description of landscape pattern of the selected locations was also discussed above (refer to chapter 4, section 4.4.1). In this segment of study, two different placement of top-flat hump were investigated. One was installed along the road and another one was at the intersection. Two different placement of hump found in the study areas are shown in Figure 5.3.

(a) Along the road (b) At intersection

Fig. 5.3 Two different placement of hump in the study area

5.4.1 Selected street section characteristics

For developing speed model, the standard geometric features that are very common in urban residential streets (Shahram *et al.*, 2014; Dinh and Kubota, 2013) almost all over the world for example; length of road, roadway width, traffic direction, sidewalk width, street marking, etc. were considered as independent variables. Detail descriptions of the selected road characteristics are summarized in Table 5.1.

Table 5.1 Summary of selected street section features

Characteristics	Measured value
Length of Street Section (m)	180 to 313; mean: 233.37
Traffic Direction	Two-way Traffic: 6 Sites; One-way Traffic: 1 Site
Roadway Width (m)	3.95 to 8.95; mean: 6.11
Carriageway Width (m)	2.75 to 6.63; mean: 4.27
No of Lanes	1 to 2; mean: 1.14
Left Safety Strip Width (m)[a]	0.5 to 1.16; mean: 0.88
Right Safety Strip Width (m)[b]	0.5 to 1.16; mean: 0.95
Presence of Sidewalk	No Sidewalk: 5 sites; Sidewalk on both side: 2 sites
Street Marking	No Marking: 1 site; Marking Present: 6 sites
Placement of Hump	Along the road: 6 sites; At intersection: 1 site

Notes: [a]Left Safety Strip Width (m) - Distance between the edges of a study lane to the curb on the left side of the target direction. [b]Right Safety Strip Width (m) - Distance between the edges of a study lane to the curb on the right side of target direction.

5.4.2 Speed data collection

A total of 487 individual speed data (refer to section 4.4.2, chapter 4) from seven locations were composed for further speed analysis.

5.5 Data Analysis

5.5.1 Model Development

For a better understanding about speed along the study road, several speed models at a distance of 10 m interval in the upstream and downstream side from hump location were derived by multiple linear regression analysis. The regression equation and assumptions were discussed in section 3.5.2 in chapter 3.

5.5.2 Dependent variable

The total study length of the selected seven locations varied from 180m to 313m. The maximum upstream length of six locations was 120m except for Nakanishi (upstream length 80m). Among the seven locations, the downstream length of four locations (Urasoe, Asaka, Okurayama, and Nakanishi) was 60m and the rest of three locations (Kita-Ageo, Miyoshi and Tsurugashima) were 30m. Speed data were measured at every 10m distance interval from the hump in both direction (upstream and downstream) and also at hump position and considered as dependent variables for analysis. Table 5.2 represents the descriptive statistics of the dependent variables.

Table 5.2 Descriptive statistics of dependent variables

Variable V_i	N	Min. speed	Max. speed	Mean speed	Standard Error Mean	Standard Deviation	Skewness	Kurtosis
V_{-120} (km/h)	440	10.00	58.86	33.64	0.44	9.33	-0.17	-0.36
V_{-110} (km/h)	440	9.90	56.92	33.87	0.43	9.08	-0.24	-0.30
V_{-100} (km/h)	440	9.19	55.48	34.00	0.41	8.63	-0.25	-0.24
V_{-90} (km/h)	440	9.18	54.29	33.81	0.39	8.13	-0.26	-0.14
V_{-80} (km/h)	487	10.02	53.33	31.71	0.39	8.60	-0.26	-0.47
V_{-70} (km/h)	487	9.13	50.00	30.80	0.37	8.24	-0.33	-0.28

Table 5.2 Descriptive statistics of dependent variables

Variable V_i	N	Min. speed	Max. speed	Mean speed	Standard Error Mean	Standard Deviation	Skewness	Kurtosis
V_{-60} (km/h)	487	9.10	47.69	29.90	0.33	7.38	-0.25	-0.17
V_{-50} (km/h)	487	9.20	45.76	28.97	0.28	6.13	-0.01	-0.14
V_{-40} (km/h)	487	14.28	45.21	27.48	0.24	5.40	0.19	0.05
V_{-30} (km/h)	487	9.80	44.77	25.40	0.23	5.05	0.33	0.60
V_{-20} (km/h)	487	10.15	43.90	22.72	0.22	4.93	0.51	0.80
V_{-10} (km/h)	487	9.01	43.54	19.36	0.23	5.03	0.87	1.77
V_0 (km/h)	487	9.09	42.07	16.60	0.25	5.42	1.04	1.92
V_{+10} (km/h)	487	9.50	42.91	19.32	0.20	4.36	1.21	3.71
V_{+20} (km/h)	487	9.66	41.96	19.19	0.25	5.45	0.71	0.75
V_{+30} (km/h)	487	9.01	41.35	18.33	0.32	7.15	0.59	-0.58
V_{+40} (km/h)	210	9.58	40.63	25.47	0.39	5.61	-0.06	0.20
V_{+50} (km/h)	210	9.19	40.07	25.68	0.40	5.83	-0.07	-0.06
V_{+60} (km/h)	210	9.33	39.96	25.31	0.42	6.05	-0.09	-0.07

Note: "V_{-i}" and "V_{+i}" indicate the speed at different upstream and downstream distance from the center of hump at 10 m intervals respectively. "V_0" indicates the speed at hump location.

From Table 5.2, it has been found that the values of the skewness and kurtosis for most of the variables except for the sections closer to hump were near zero. This showed that the data were normally distributed (Zainuddin *et al*., 2014).

5.5.3 Speed model estimation

The geometric roadway and roadside characteristics have been considered as independent variables in this study e.g., length of study street section, no. of lane, carriageway width, the presence of sidewalk, two-way traffic etc. Moreover, in these models the speed at 10m distance before the dependent variable was taken as an independent variable. For example, if the dependent variable of a model is speed at 10m distance before hump (V-i = V-10 km/h; where V-i indicate the speed at different upstream distance from hump), then the speed at 20m distance before hump (i.e. V-i = V-20 km/h) has been inserted as an independent variable in regression equation. Similarly, for V-20 km/h speed model V-30 km/h has been considered as an independent variable and so on. On the other hand, the speed at 120m distance upstream has been assumed as the entry speed for each vehicle. Therefore, no regression model has been developed for 120m. Table 5.3 represents the regression analysis results for estimating speed at a distance of 110m upstream of hump to 60m downstream of hump.

Table 5.3 Speed estimating models at a distance of 70m to 110m upstream of hump

Variable	Estimated Coefficient	t-ratio	sig	Adj R^2	Sample Size
Dependent Variable: Logarithm of speed at 110m distance before hump ($Ln\ V_{-110}$) (km/h)					
Constant	0.138	4.950	0.000***	0.976	440
Street Marking (1 = yes, 0 = otherwise)	-0.039	-3.934	0.000***		
Logarithm of speed at 120m distance before hump (km/h)	0.974	118.801	0.000***		
Dependent Variable: Logarithm of speed at 100m distance before hump ($Ln\ V_{-100}$) (km/h)					
Constant	0.224	4.408	0.000***	0.960	440
Street Marking (1 = yes, 0 = otherwise)	-0.026	-2.122	0.034*		
Logarithm of speed at 110m distance before hump (km/h)	0.939	74.825	0.000***		
Dependent Variable: Logarithm of speed at 90m distance before hump ($Ln\ V_{-90}$) (km/h)					
Constant	0.309	6.446	0.000***	0.934	440
Logarithm of speed at 100m distance before hump (km/h)	0.915	70.848	0.000***		
Dependent Variable: Logarithm of speed at 80m distance before hump ($Ln\ V_{-80}$) (km/h)					
Constant	-0.025	-0.608	0.044*	0.945	487
Street Marking (1 = yes, 0 = otherwise)	-0.065	-5.710	0.000***		
Logarithm of speed at 90m distance before hump (km/h)	1.017	84.928	0.000***		
Dependent Variable: Logarithm of speed at 70m distance before hump ($Ln\ V_{-70}$) (km/h)					
Constant	0.1	2.143	0.033*	0.927	487
Two way (1= Two way, 0 = One way)	-0.052	-2.903	0.004**		
Street Marking (1 = yes, 0 = otherwise)	-0.061	-4.175	0.000***		
Logarithm of speed at 80m distance before hump (km/h)	0.993	66.465	0.000***		

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.0001$

Table 5.3 Speed estimating models at a distance of 60m to 30m upstream of hump

Variable	Estimated Coefficient	t-ratio	sig	Adj R^2	Sample Size
Dependent Variable: Logarithm of speed at 60m distance before hump ($Ln\ V_{-60}$) (km/h)					
Constant	0.437	9.992	0.000***	0.917	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.031	3.571	0.000***		
Logarithm of speed at 70m distance before hump (km/h)	0.864	72.583	0.000***		
Dependent Variable: Logarithm of speed at 50m distance before hump ($Ln\ V_{-50}$) (km/h)					
Constant	0.713	17.838	0.000***	0.905	487
Two way (1= Two way, 0 = One way)	-0.131	-10.811	0.000***		
Hump along the road (1 = yes, 0 = otherwise)	-0.023	-1.990	0.047*		
Logarithm of speed at 60m distance before hump (km/h)	0.824	64.183	0.014*		
Dependent Variable: Logarithm of speed at 40m distance before hump ($Ln\ V_{-40}$) (km/h)					
Constant	0.197	3.202	0.001**	0.899	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.09	7.122	0.000***		
Two way (1= Two way, 0 = One way)	-0.193	-11.755	0.000***		
Right Safety Strip Width (m)	0.096	7.056	0.000***		
Sidewalk Presence (1 = Both side of road, 0 = one side or no sidewalk)	0.03	2.713	0.007**		
Hump along the road (1 = yes, 0 = otherwise)	-0.065	-5.199	0.000***		
Logarithm of speed at 50m distance before hump (km/h)	0.951	55.653	0.000***		
Dependent Variable: Logarithm of speed at 30m distance before hump ($Ln\ V_{-30}$) (km/h)					
Constant	-0.122	-2.509	0.012*	0.917	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.147	13.913	0.000***		
Two way (1= Two way, 0 = One way)	-0.270	-16.189	0.000***		
Right Safety Strip Width (m)	0.153	13.386	0.000***		
Lane (1 = One lane, 0 = otherwise)	-0.070	-7.105	0.000***		
Hump along the road (1 = yes, 0 = otherwise)	-0.080	-7.177	0.000***		
Logarithm of speed at 40m distance before hump (km/h)	1.058	69.357	0.000***		

Note: * p<0.05, ** p<0.01, *** p<0.0001

Table 5.3 Speed estimating models at a distance of 20m upstream to 0m or hump

Variable	Estimated Coefficient	t-ratio	sig	Adj R^2	Sample Size
Dependent Variable: Logarithm of speed at 20m distance before hump (Ln V_{-20}) (km/h)					
Constant	-0.132	-2.483	0.013*	0.901	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.139	12.155	0.000***		
Two way (1= Two way, 0 = One way)	-0.251	-14.045	0.000***		
Right Safety Strip Width (m)	0.166	13.332	0.000***		
Lane (1 = One lane, 0 = otherwise)	-0.071	-6.332	0.000***		
Hump along the road (1 = yes, 0 = otherwise)	-0.098	-7.575	0.000***		
Logarithm of speed at 30m distance before hump (km/h)	1.048	64.909	0.000***		
Dependent Variable: Logarithm of speed at 10m distance before hump (Ln V_{-10}) (km/h)					
Constant	-0.202	-2.612	0.009**	0.797	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.100	5.405	0.000***		
Two way (1= Two way, 0 = One way)	-0.235	-8.479	0.000***		
Right Safety Strip Width (m)	0.156	8.372	0.000***		
Lane (1 = One lane, 0 = otherwise)	-0.07	-3.851	0.000***		
Logarithm of speed at 20m distance before hump (km/h)	1.031	42.484	0.000***		
Dependent Variable: Logarithm of speed at 0m or at hump location (Ln V_0) (km/h)					
Constant	-0.279	75.082	0.001**	0.793	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.052	2.246	0.025*		
Two way (1= Two way, 0 = One way)	-0.186	-5.335	0.000***		
Right Safety Strip Width (m)	0.077	3.316	0.001**		
Lane (1 = One lane, 0 = otherwise)	-0.047	-2.080	0.038*		
Logarithm of speed at 10m distance before hump (km/h)	1.071	41.047	0.000***		

Note: * p<0.05, ** p<0.01, *** p<0.0001

Table 5.3 Speed estimating models at a distance of 10m to 60m downstream of hump

Variable	Estimated Coefficient	t-ratio	sig	Adj R^2	Sample Size
Dependent Variable: Logarithm of speed at 10m distance after hump (Ln V_{+10}) (km/h)					
Constant	1.781	26.115	0.000***	0.600	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.065	2.953	0.003**		
Two way (1= Two way, 0 = One way)	-0.149	-4.279	0.000***		
Lane (1 = One lane, 0 = otherwise)	-0.155	-7.155	0.000***		
Logarithm of speed at 0m or at hump position (km/h)	0.491	23.983	0.000***		
Dependent Variable: Logarithm of speed at 20m distance after hump (Ln V_{+20}) (km/h)					
Constant	1.101	9.155	0.000***	0.688	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.354	13.762	0.000***		
Two way (1= Two way, 0 = One way)	-0.636	-15.476	0.000***		
Right Safety Strip Width (m)	0.373	13.415	0.000***		
Lane (1 = One lane, 0 = otherwise)	-0.260	-10.162	0.000***		
Hump along the road (1 = yes, 0 = otherwise)	-0.351	-11.833	0.000***		
Logarithm of speed at 10m distance after hump (km/h)	0.805	22.598	0.000***		
Dependent Variable: Logarithm of speed at 30m distance after hump (Ln V_{+30}) (km/h)					
Constant	-0.718	-8.805	0.000***	0.846	487
Street Length (m) (1 = ≥ 200m, 0 = otherwise)	0.100	6.482	0.000***		
Right Safety Strip Width (m)	0.070	3.666	0.000***		
Hump along the road (1 = yes, 0 = otherwise)	-0.155	-5.564	0.000***		
Logarithm of speed at 20m distance after hump (km/h)	1.226	49.315	0.000***		
Dependent Variable: Logarithm of speed at 40m distance after hump (Ln V_{+40}) (km/h)					
Constant	0.176	2.370	0.019*	0.891	210
Logarithm of speed at 30m distance after hump (km/h)	0.952	40.891	0.000***		
Dependent Variable: Logarithm of speed at 50m distance after hump (Ln V_{+50}) (km/h)					
Constant	0.163	1.882	0.041*	0.865	210
Logarithm of speed at 40m distance after hump (km/h)	0.955	36.146	0.000***		
Dependent Variable: Logarithm of speed at 60m distance after hump (Ln V_{+60}) (km/h)					
Constant	-0.034	-.384	0.001**	0.878	210
Logarithm of speed at 50m distance after hump (km/h)	0.977	31.867	0.000***		

Note: * p<0.05, ** p<0.01, *** p<0.0001

5.5.4 Analysis of variance for speed model

The analysis of variance (ANOVA) of the output of regression models are shown in Table 5.4 and 5.5.

Table 5.4 Analysis of variance for speed models V_{-110} km/h to V_{-30} km/h

Model (km/h)	V_{-110}	V_{-100}	V_{-90}	V_{-80}	V_{-70}	V_{-60}	V_{-50}	V_{-40}	V_{-30}
F-test	4337.8	2613.8	1530.1	2511.7	1218.4	1334.0	1530.9	710.7	885.0
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5.5 Analysis of variance for speed models V_{-20} km/h to V_{+60} km/h

Model (km/h)	V_{-20}	V_{-10}	V_{0}	V_{+10}	V_{+20}	V_{+30}	V_{+40}	V_{+50}	V_{+60}
F-test	724.7	377.6	369.5	119.8	176.6	659.8	842.2	661.0	367.3
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

From Table 5.4 and 5.5, it can be seen that the p-value for all developed models was less than 0.05; hence the regression models were significant and could be used to predict speed of other locations where hump will be installed.

5.6 Model Validation

This part of the current research checks the validity of the developed regression models described in table 3, by using a new data set. The new data set were used to examine how well the developed model will perform on the independent data set. The consistency of the results will reveal that the regression models are relevant under broader circumstances (Kutner *et al.*, 2005). Therefore, the independent data were collected from a new location Nakayama in Kanagawa prefecture. The selected street section has the same geometric configurations as the previous study locations i.e. street marking, two-way traffic, one lane etc. The selected road is located in residential areas with a speed limit of 30km/h and having residential neighborhood along both sides of the road. The study length is 220m. The field speeds were measured directly by using ATS radar gun same as previous locations. Total 43 individual speed profiles were collected from the study location to check the validity of developed models.

5.6.1 Dependent variable

The upstream and downstream length of Nakayama is 120m and 100m respectively. To maintain the order of previously developed models, the downstream length of Nakayama was considered up to 60m. Therefore, the upstream length is divided into 12 sections and the downstream length is divided into 6 sections and the speed data measured at these sections were considered as dependent variables. Table 5.6 summarizes the descriptive statistics of the dependent variables of Nakayama.

Table 5.6 Descriptive statistics of dependent variables of Nakayama

Variable (V_i)	Sample Size	Minimum	Maximum	Mean	Standard Error Mean	Standard Deviation
V_{-120} (km/h)	43	20.60	36.70	29.29	0.62	4.06
V_{-110} (km/h)	43	25.78	39.61	32.00	0.58	3.78
V_{-100} (km/h)	43	26.47	39.82	33.23	0.56	3.67
V_{-90} (km/h)	43	27.34	41.22	33.85	0.58	3.81
V_{-80} (km/h)	43	26.94	42.21	33.91	0.59	3.85
V_{-70} (km/h)	43	24.47	43.15	33.45	0.62	4.05
V_{-60} (km/h)	43	23.28	43.34	33.03	0.67	4.40
V_{-50} (km/h)	43	21.61	43.16	32.11	0.69	4.51
V_{-40} (km/h)	43	16.82	42.35	31.05	0.87	5.68
V_{-30} (km/h)	43	14.49	41.12	30.34	1.02	6.66
V_{-20} (km/h)	43	13.59	41.49	29.71	1.02	6.67
V_{-10} (km/h)	43	16.42	42.20	29.26	0.96	6.30
V_0 (km/h)	43	11.5	42.48	28.46	1.09	7.14
V_{+10} (km/h)	43	14.94	42.12	28.68	1.03	6.72
V_{+20} (km/h)	43	16.94	41.67	29.96	0.83	5.41
V_{+30} (km/h)	43	19.3	42.01	31.03	0.78	5.13
V_{+40} (km/h)	43	21.53	42.07	31.26	0.70	4.61
V_{+50} (km/h)	43	22.31	42.56	31.28	0.66	4.36
V_{+60} (km/h)	43	19.79	42.47	31.50	0.69	4.53

Note: "V_{-i}" and "V_{+i}" indicate the speed at different upstream and downstream distance from the center of hump at 10 m intervals respectively. "V_0" indicates the speed at hump location.

5.6.2 Prediction model

The predicted speed of Nakayama at every 10m distance interval in upstream and downstream of hump as well as at hump location were estimated by using equation (3), where the independent variables are selected based on the regression models developed in Table 5.3 to 5.5. The equation for predicting speed at different distance of Nakayama is as follows

$$\ln V_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots\ldots + \ln V_{(i-1)} + \varepsilon \qquad (3)$$

wherein,

- V_i = vehicle speed at ith distance from hump (km/h),
- $V_{(i-1)}$ = vehicle speed at (i-1)th distance from hump (km/h),
- x_1, x_2 = vectors of significant independent variables derived from regression models; representing different street features,
- β_0 = estimable parameter(constants),
- ε = disturbance terms, and
- β_1, β_2 = estimable parameters (Coefficients of independent variables to be calculated)

5.6.3 Validation analysis

The accuracy of the predicted models was estimated by checking the values of Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Mean Absolute Percentage error (MAPE), derived from the following equations

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(y-yi)^2}{N}} \qquad (4)$$

$$\text{MAE} = \frac{\sum_{i=1}^{N}|y-yi|}{N} \qquad (5)$$

$$\text{MAPE} = \frac{\frac{\sum_{i=1}^{N}|y-yi|}{y}\times 100}{N} \qquad (6)$$

Where yi is the predicted value from the developed models for the i^{th} data set; y is the field value for i^{th} data set and N is the number of data set considered.

Table 5.7 summarizes the comparisons of RMSE, MAE, and MAPE of all the predicted models. It showed that all models had a small value for RMSE, MAE, and MAPE. Therefore the developed models can be accepted and predict the good result. According to Zainuddin *et al*. (2014), the prediction would be good if the values of RMSE, MAE, and MAPE become smaller. An exception of the above results have been found in the speed models near to hump locations i.e. at the distance of 10m upstream to 20m downstream of hump; where the RMSE value is a little bit bigger (4.26 to 6.21) than others. The possible reason may be the high efficiency of a hump in reducing vehicle speed at hump location. A standard speed hump forces drivers to slow down their speed at hump location even though the upstream speed was higher, which create the variations in speed data within a short interval of distances like 10m.

Table 5.7 Validation analysis results for the predicted speed models

Model	RMSE	MAE	MAPE
V_{-110} (km/h)	2.89	2.56	8.07
V_{-100} (km/h)	2.00	1.77	5.31
V_{-90} (km/h)	1.09	0.90	2.71
V_{-80} (km/h)	1.58	1.39	4.20
V_{-70} (km/h)	1.57	1.35	4.11
V_{-60} (km/h)	1.62	1.15	3.67
V_{-50} (km/h)	2.17	1.83	5.67
V_{-40} (km/h)	3.09	2.32	8.36
V_{-30} (km/h)	2.26	1.75	6.39
V_{-20} (km/h)	2.88	2.50	8.80
V_{-10} (km/h)	5.01	4.50	15.79
V_{0} (km/h)	4.32	3.89	14.53
V_{+10} (km/h)	6.21	5.34	17.43
V_{+20} (km/h)	4.26	3.61	11.98
V_{+30} (km/h)	3.32	2.79	9.07
V_{+40} (km/h)	1.70	1.23	4.16
V_{+50} (km/h)	1.71	1.26	4.28
V_{+60} (km/h)	3.91	3.71	11.76

5.7 Model Interpretations and Discussions

Brief interpretations about the results for regression models, predicted models and valid models are discussed below:

5.7.1 Regression Models

(i) Speed models at the upstream side of hump

From the regression analysis, it can be seen that the vehicle speed within a 10m distance (V_{-10} km/h) to 50m distance (V_{-50} km/h) upstream from hump are positively influenced by the length of study streets and the width of right safety strip. Moreover, car speeds are negatively associated with the number of lane and two-way movement of traffic. The effects of these influential factors are consistent with the findings of Rahman *et al*. (2017). Along with the other geometric features, the placement of a single hump has also been found as a significant speed reducing factor. According to the analysis results, hump installed along the road induces a lower speed rather than installed at intersection. Furthermore, from the regression models, it is the evident that the dependent variables are strongly influenced by the speed of the previous sections i.e. if the speed at a 20m distance before hump (V_{-20} km/h) increased, V_{-10} km/h will also increase by 1.031σ or 5.2 km/h. Similarly, speed within 20m to 50m distance before hump will increase by 5.16km/h to 5.1km/h due to the increasing speed at 30m to 60m distance upstream correspondingly.

In the case of 40m upstream, the presence of sidewalk on both side of road resulted in a higher speed value. The possible explanation of this positive effect is that; the presence of sidewalk increases driver's perception regarding road safety and encourages them to speed up (Dinh and Kubota, 2013).

The speed models at a 60m (V_{-60} km/h) to 110m (V_{-110} km/h) distance before hump showing a different result from the previous sections. The effect of the hump is totally disappeared after 60m distance from the hump. Which indicates that hump is effective in reducing vehicle speed within the Zone of Influence area (The zone of influence (ZoI) is the area over which vehicle speed reducing effect occurs under the application of traffic calming device Daniel *et al*. (2011)). Furthermore, these models also show the higher speed values as the speed of previous sections become high. Conversely, speed at a distance of 60m to 110m upstream of hump is negatively associated with street marking. In case of visible road marking; speed decreases by 0.065σ (0.54 km/h) to 0.035σ (0.35 km/h) within 70m to 110m distance upstream from hump.

(ii) Speed model at hump location

The regressions results show that hump speed increased by 0.052σ (0.282 km/h) if the length of road is more than 200m. As expected, a longer length resulted in higher values for speeds.

Likewise, upstream models hump speed also influenced by two-way traffic, number of lane, right safety strip width and speed at the previous section.

(iii) Speed models at the downstream side of hump

The downstream speed up to a 30m distance from hump decreased by the significant influence of placement of hump, number of lanes and two-way traffic. From the models, it has been found that the speed within 10m (V_{+10} km/h) to 30m (V_{+30} km/h) distance after hump also influenced positively by the speed at previous section similar to upstream speed.

The regression models developed within 40m (V_{+40} km/h) to 60m (V_{+60} km/h) distance from the hump reveal that the car speed in these sections are only influenced by the speed of previous sections i.e. speed at 40m (V_{+40} km/h) distance increases by 0.952σ (5.34 km/h), speed at 50m (V_{+50} km/h) increases by 5.6km/h and speed at 60m (V_{+60} km/h) increases by 5.91 km/h if speed at 30m to 50m distance downstream increase respectively.

5.7.2 Prediction Models

The relationship between the field speed and predicted speed of Nakayama has been assembled by using a scatter plot. A 45-degree line is drawn in the graphs as a reference line to check how much the predicted values matched with the field values. Figure 5.4 presents the scatter plots of speed models at a distance of 20m (V_{-20} km/h) to 110m (V_{-110} km/h) upstream of hump to show the relationship. From the figure it has been observed that, In case of 20m to 80m upstream of hump; the points were randomly scattered along the 45-degree line, which means that the predicted values are matched with the field values and the models developed within the distance of 20m to 80m upstream of hump are perfect (Zainuddin *et al.*, 2014). In case of 90m to 110m upstream; the points were slightly lower than the reference line. Though there is an intersection and also a pedestrian crossing at the entrance point but the field speed was found high in Nakayama compare to other residential streets.

Figure 5.5 illustrates the relationship between the field speed and predicted speed estimated near the hump location (i.e. at a distance of 10m upstream to 0m of hump or at hump point). These models (V_{-10} km/h and V_0 km/h) are accurate as the points were scattered along the reference line.

From figure 5.6 it is found that, in case of 10m to 30m downstream of hump; the points were far from the reference line. Here the figure shows lower predicted speed values for higher field values. The possible explanation is that, there is slope a at 80m distance from hump in the downstream side at Nakayama. Therefore, drivers may accelerate due to this slope just after crossing the hump. It may depend on driver’s perception. On the other hand, in case of 40m (V_{+40} km/h) to 60m (V_{+60} km/h) downstream of hump the developed models were perfect, as the points of all models were observed very close to the 45-degree line.

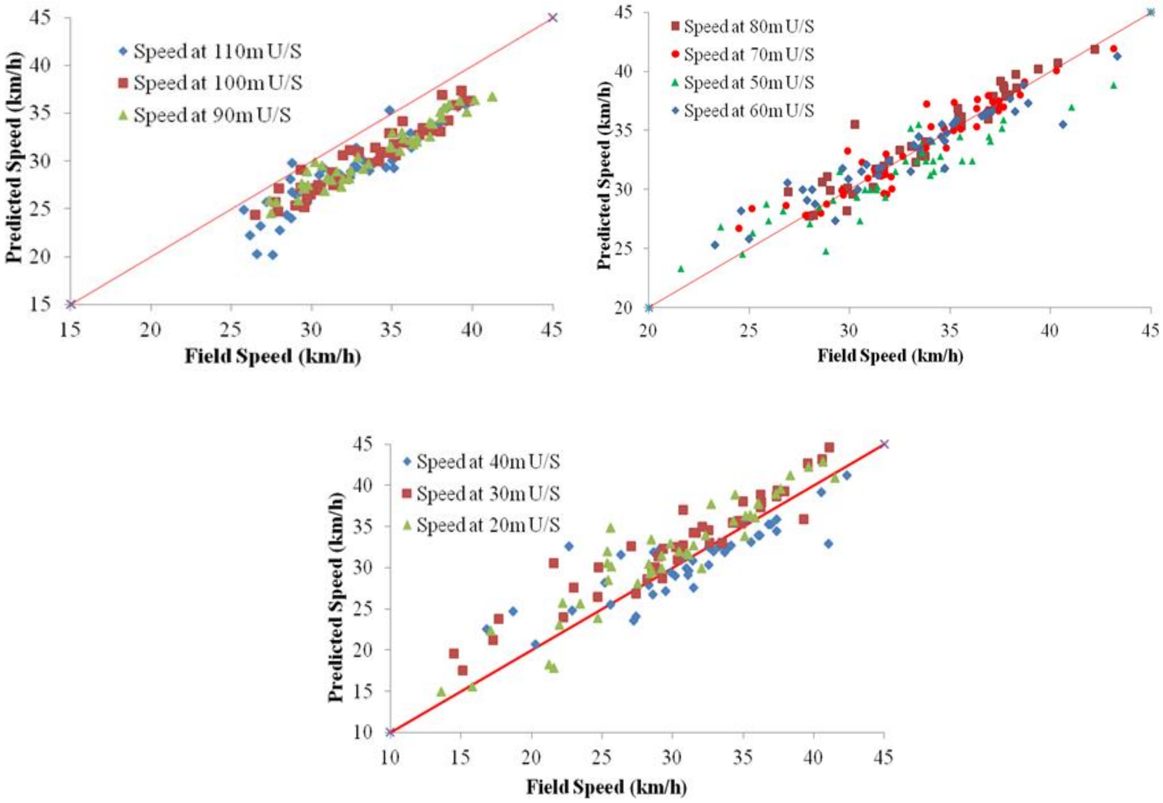


Fig. 5 4 Relationship between field speed and predicted speed of model V_{-20} km/h to V_{-110} km/h

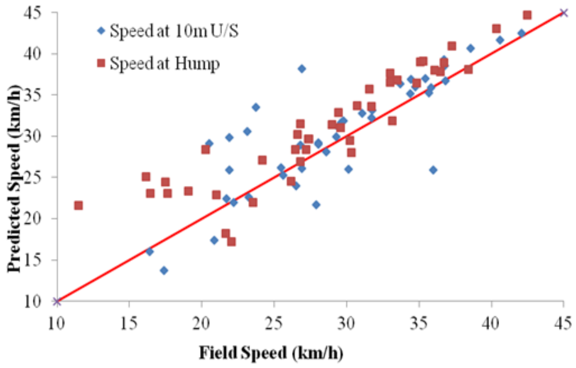


Fig. 5.5 Relationship between field speed and predicted speed of model V_{-10} km/h and V_0 km/h

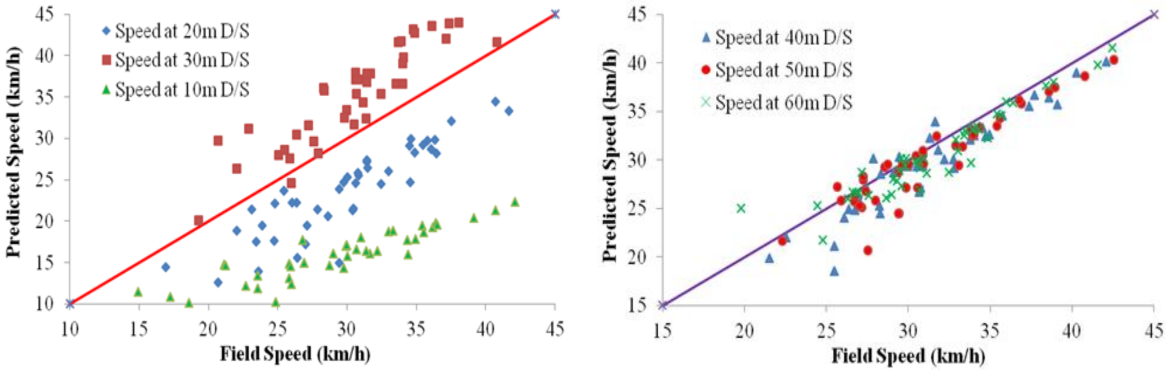


Fig. 5 6 Relationship between field speed and predicted speed of model V_{+10} km/h to V_{+60} km/h

5.7.3 Validated Models

Table 5.8 represents the comparison of RMSE values calculated by using equation (4); between the car speed exceed 35 km/h and car speed lower than 35 km/h of Nakayama street. It has been observed that, among the 43 independent vehicle speed data, 26 cars have maximum speed above 35 km/h and 17 cars drive slower than that. Nonetheless the RMSE values are smaller, revealed a bigger value for high speed car compared to low speed car as well as the variance. From the predicted models it also found that, for low speed car the models can predict speed from 29 km/h to 34 km/h whereas for higher speed values the predicted speed will be from 36 km/h to 50 km/h. Therefore, by using these prediction models further improvement in speed data can be made which will help urban planners to establish the placement of hump and maintain a lower speed level along the entire road section.

Table 5.8 Comparison of RMSE values for car speed exceed or less than 35 km/h of Nakayama

Maximum Field speed	Sample Size	Maximum Predict speed	RMSE Range	Mean	Variance
> 35.01 km/h	26	36 to 47 km/h	5.34 to 2.32	3.26	0.53
< 35 km/h	17	29 to 34 km/h	3.59 to 1.73	2.61	0.28

5.8 Conclusions

The speed reduction characteristics in the upstream and downstream side of a single speed hump as well as at the location of hump have been examined successfully in this segment of the current research using multiple linear regression analysis. Various road geometric features e.g., street marking, traffic direction, number of lane, safety strip width, placement of hump etc. found to be significant predictors for vehicle speed reduction. Nonetheless, a novel factor; the speed at the previous section (V_{i-1} km/h) of the dependent variable (V_i km/h) was inserted in the regression analysis as an independent variable and found as a considerable speed influencing factor. A prediction model also developed with an independent data set which was further used to check the validity of regression models. Regarding the results of the validation analysis demonstrated in table 5.6 and 5.7; the developed regression models can be accepted.

The models developed in this study are applicable for urban residential streets shaving 30 km/h speed limit where a single hump is present. The desired predicted speed of an individual vehicle for a neighborhood street where hump will be installed can be estimated by using equation (3). For example, if the total length of a residential road is 180m and the entry speed of a car into that road is 40 km/h (V_{-120} km/h), the desired speed in the upstream side of hump at every 10m distance interval from the entry point is about 40 km/h (V_{-110}), 39 km/h (V_{-100}), 38 km/h (V_{-90}), 37 km/h (V_{-80}), 36 km/h (V_{-70}), 35 km/h (V_{-60}), 33 km/h (V_{-50}), 31 km/h (V_{-40}), 30 km/h (V_{-30}), 28 km/h (V_{-20}), 24 km/h (V_{-10}); speed at hump is 20 km/h (V_0) and speed in downstream is 20 km/h (V_{+10}), 20 km/h (V_{+20}), 20 km/h (V_{+30}), 20 km/h (V_{+40}), 21 km/h (V_{+50}), 19 km/h (V_{+60}) respectively. Assuming the road has one lane and two-way movement of traffic, having 1.0m right safety strip width and the hump is located along the road section. Furthermore, the developed models can be used to maintain a lower speed level along the entire road section by installing a single hump in a suitable position if the residential streets contain the standard geometric configurations.

In addition, though the entry speed is higher than the existing speed limit; the relationship between vehicle speed and the roadway and roadside characteristics developed in this study provide helpful information to the practitioners to understand the speed reduction mechanism of a single hump in case of longer road section (i.e. 200m to 300m) and also help to find out the optimum placement of a single hump. The outcome of this study is meaningful and the authors hope that it can be used to implement and enhance the guidelines and standards of installing hump in such kind of residential streets.

CHAPTER 6

Conclusion and Recommendation

6.1 Conclusions

Residential streets or neighborhood streets are particularly designed to serve the local residents efficiently and work as the backbone of the built environment. Therefore, residential streets should be safe and secure for all road users. To ensure safety in a residential neighborhood, excessive speed is inappropriate for such kind of roads as people perceived risk due to a higher speed. A speed limit of 30 km/h has been widely introduced as an enforcement measure in most of the residential streets in Japan to overcome the speeding problems. Despite the settings of posted speed limit, excessive speeds are found very common on these roads. Furthermore, a physical device such as speed hump has been introduced as a traffic calming measure along with enforcement measure (30 km/h speed limit) to maintain a lower speed along the road. However, some uncertainties were observed regarding the speed reduction caused by the installed hump. This present dissertation was therefore designed to explore the speeding mechanism on residential streets having 30 km/h speed limit with the presence of a single speed hump along the road by considering the combined effect of street environment or street features and hump. Specifically this research focuses on several purposes like (i) to identify the external factors (based on road geometry) affecting the effectiveness of speed hump; (ii) to investigate the external geometric and non-geometric factors associated with the speed reduction in the upstream of humps; (iii) to identify the suitable position of a single hump to maintain a lower speed along the entire length of the road; and (iv) To predict individual vehicle speed profile of a residential neighborhood where a hump will be installed.

6.2 Speeding Problems in Residential Streets

In this research, free flow speed survey was conducted on a variety of street sections containing various road characteristics and where a single speed hump is present. All of the selected roads were located in urban residential areas having 30 km/h speed limit. The analysis result confirmed that speeding is very common on these roads even after installation of speed hump. In this study it has found that about 38% drivers maneuvered their vehicles at a speed of 40 km/h or more on streets with a 30 km/h speed limit. Therefore, more attentions are needed on speed reduction to ascertain traffic safety in residential neighborhoods in Japan.

6.3 Street Features and Driving Speeds on a Traffic Calmed Street

The present dissertation established a relationship between road features and vehicle speed on residential street where a single speed hump is present and the roads having 30 km/h speed limit by developing numerous operating speed models at different locations along the road. Continuous speed data were collected for individual vehicles by using STALKER ATS radar gun from different residential streets in Japan. According to Dinh and Kubota (2013), for better understanding about the mechanism of driving speed along the entire length of road it is necessary to conduct a profile-speed survey rather than spot-speed survey. Therefore, this study used profile speed data of individual vehicles for analyzing purpose.

In this research, basically three speed models were developed at different locations along the study roads to explore the speed characteristics. A multiple linear regression analysis was used for the modeling effort.

In the first speed model, speed data were collected from 20 different neighborhood streets in Tokyo prefecture in Japan where the maximum length of the roads were around 200m. In this model, individual car speed data at the location of hump was considered as dependent variable and other road geometric features were inserted as independent variables in the regression equation. To understand the actual effect of the road features over speed, the independent variables were further divided into two categories named "Basic factors" and "Sub-factors" where the "Basic factors" representing their natural existence on road and "Sub-factors" indicating the presence of "Basic factors" on street at different distance from hump. The regression results showed that as a "Basic factors"; the length of the road, presence of intersection, parking and crossing have positive effect on driving speed at the location of hump whereas shape of hump has negative effect. In addition, the developed model based on sub factors specifically stated that 20m distance has a significant influence over car speed i.e. if any hump installed at a distance of 20m vicinity of any unsignalized T intersection; vehicle speed would reduce more effectively.

As, the first speed model was limited to examine the speed at hump location only, more operating speed models were developed for research purpose at every 10m distance interval in the upstream side of device to better understand the speed reduction characteristics of urban roads. For this part, speed data were collected from 7 different residential roads in Japan where the maximum length of the roads were around 300m. Here, the regression results again revealed that the shape of the hump and the intersection density at a distance of 20m vicinity of hump has strong negative influence over car speed like the previous model of this study. The developed models further confirmed the effectiveness of speed hump until the Zone of Influence area (ZoI) and concluded that after ZoI area street features affect the driving speed more than that of a hump. Nonetheless, a novel non-geometric factor named "street with many pedestrians" was also introduced as a significant speed reducing factor in these models.

In the last part of this dissertation, the speed models were developed based on individual vehicle's speed data in the upstream and downstream side of a single speed hump as well as at the location of hump by using the same procedure as discussed above. These models also showed the effect of road characteristics as significant predictors for vehicle speed reduction. Furthermore, the results concluded that speed at any 10m distance from the device is highly correlated with the speed at its previous 10m distance. Here, a prediction model was also developed to predict vehicle speed at every 10m distance interval of a residential road; where a single hump is present and then this model was validated with an independent data set. The validation analysis revealed that the developed models are accurate and can be used in future prediction.

According to the findings stated above it can be concluded that driving speed in urban residential streets where a single speed hump is present is associated with several external factors. For better understanding, the external factors can be divided into following categories:

1. Geometric Features within ZoI

- Length of road, width of right safety strip and both sided sidewalk has positive effect on vehicle speed
- Two way traffic, one lane road, street marking and shape of hump has negative effect on vehicle speed
- Due to the presence of un-signalaized T intersection within 20m to 40m vicinity of hump; the speed reduction rate increases

2. Geometric Features outside ZoI

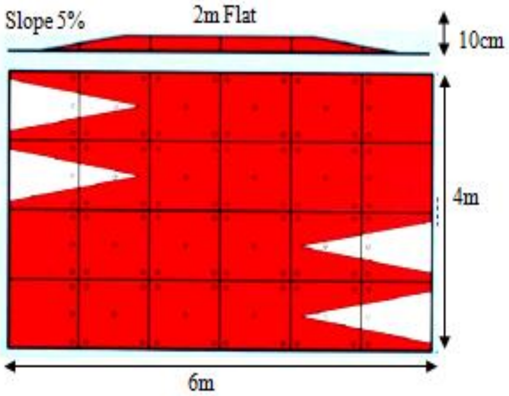
- Study length, street marking and traffic direction has influence over car speed.
- After ZoI area the effect of hump disappear in the developed models. Which indicated that hump is effective in reducing speed until its ZoI area.

3. Non-Geometric Features

- A non-geometric factor named "street with many pedestrian" was found as a significant speed reducing factor, which indicated that pedestrian activity on road may induce drivers to move slowly.
- Moreover, another factor named "the speed at the previous section (V_{i-10}m km/h) of the dependent variable (V_i km/h) " was found as a considerable speed influencing factor.

4. Shape of Hump

- Top flat hump with sinusoidal curve in slope is more effective in reducing vehicle speed than other type of hump.



Top-Flat Hump (Sinusoidal Curve)

5. Placement of Hump

- According to the research findings, it has been found that if hump installed along the road it becomes more efficient to maintain lower speed in case of the longer length of road.

Hump - along the road

6. Hump Installation Criteria

According to the findings of the current dissertation the following criteria might be applied for installing a single speed hump on urban road:

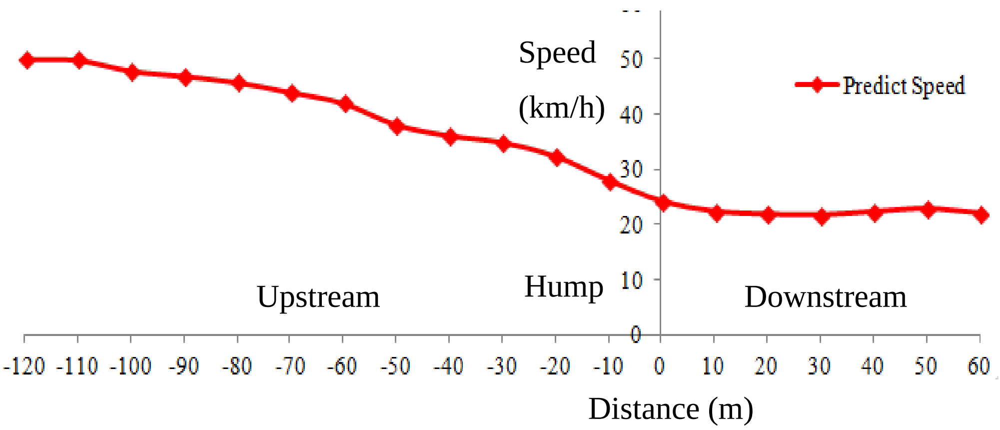
- The urban road should contain the standard road geometric features of residential streets
- The road should be close to any station or school or any places where pedestrian activity occurs most
- At the entrance of road there should be an intersection or hump sign or any other speed control measures to maintain the vehicle's entry speed lower
- Shape of hump should be fixed

Practical Application

The findings of this study can help practitioners to understand comprehensively the speed reduction mechanism of a single speed hump in case of longer road section (i.e. 200m to 300m) instead of installing multiple humps and also help to find out the optimum placement of a single hump. These models also provide a transparent perception to the residents about the speed reduction in urban streets. The prediction models developed in this study are also applicable for urban residential streets having 30 km/h speed limit where a single hump is present. The desired predicted speed of an individual vehicle for a neighborhood street where hump will be installed can be estimated by using the prediction models. For an example, if anyone wants to install a speed hump in an urban residential street where the road length is 220m, it has one lane with two-way movement of traffic and having 1m right safety strip width; then the predicted speed of any individual car on that road could be the following:

Predict Speed Profile of a car having 50km/h entry speed

Distance	Entry Speed (assume 50 km/h)	
	ln	km/h
-120	3.91	50.00
-110	3.91	49.86
-100	3.87	47.89
-90	3.85	46.95
-80	3.82	45.81
-70	3.78	44.02
-60	3.74	42.01
-50	3.64	38.06
-40	3.59	36.08
-30	3.55	34.87
-20	3.48	32.30
-10	3.33	27.99
0	3.19	24.18
10	3.11	22.33
20	3.08	21.79
30	3.07	21.65
40	3.10	22.27
50	3.13	22.80
60	3.02	22.00



Predicting Speed Profile of an Individual Car

Finally, the outcome of this study is meaningful and the authors hope that it can be used to implement and enhance the guidelines and standards of installing hump in such kind of residential streets.

6.4 Recommendations

The present research is confined to discuss about the effect of street features on driving speed in a traffic calmed street. Further research, should consider the combine effect of human factors and street features on speeding behavior to form a more comprehensive speeding mechanism where hump is present. In addition, future works should also focus on driver's behavior regarding hump. The author considered the difference between speed at every 10m distance of hump and speed at the location of hump as a dependent variable in the regression equation to observe the drivers attitude in a traffic calmed street. But the analysis output was not so much effective. There might be other factors also related with this issue. Future research should consider this more precisely. On the other hand, this study focused on only single speed hump. In the case of multiple humps, further study is needed to observe the speed reduction characteristics of residential roads. However, this study confirmed that the ZoI area of hump is varying according to the shape of hump and is ranged between 60m upstream to 70m downstream. Future study should conduct to investigate the reason for this variation between the ranges of ZoI area of the different types of hump. Furthermore, the current study was conducted on residential streets in Japan; it is needed to extend this study in other Asian countries such as Indonesia, Malaysia, etc. having similar road geometry to check the validity of the developed models. Obviously, car speed is highly correlated with the driver's choice and the driver's attitude toward speed varying from country to country. Therefore, developing speed models in the residential neighborhood of other Asian countries where hump is installed should be considered as a future study.

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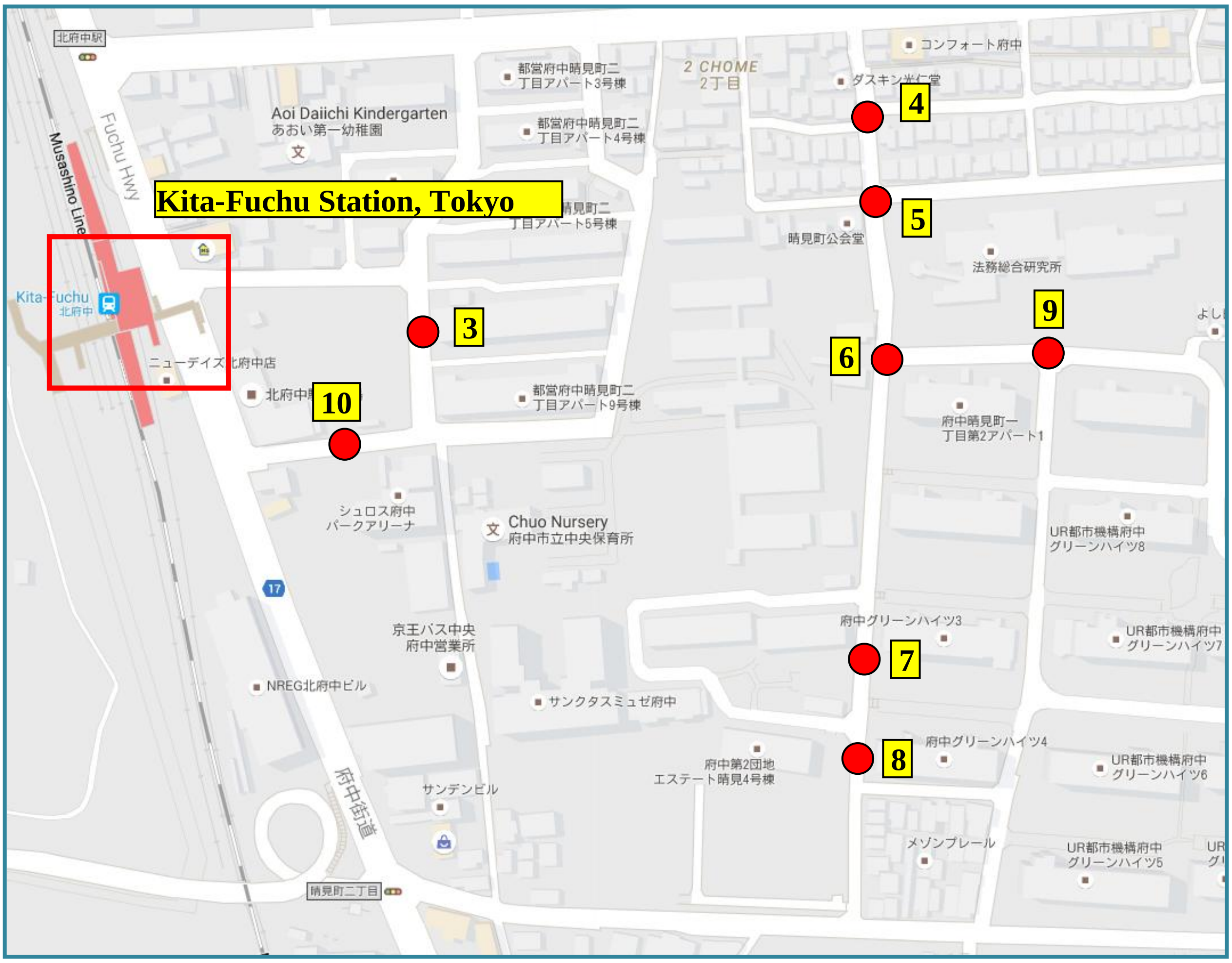
APPENDIX A

Locations of Selected Street Sections for Profile-Speed Survey

Bunkyo – Site no 1 (35°42'55.0"N 139°45'03.3"E) and Site no 2 (35°42'51.4"N 139°45'00.1"E)

Fuchu – Site no 3 (35°40'50.3"N 139°28'23.9"E), Site no 4 (35°40'53.5"N 139°28'32.1"E), Site no 5 (35°40'52.3"N 139°28'32.2"E), Site no 6 (35°40'50.0"N 139°28'32.4"E), Site no 7 (35°40'45.6"N 139°28'32.0"E), Site no 8 (35°40'44.0"N 139°28'31.8"E), Site no 9 (35°40'49.9"N 139°28'35.2"E) and Site no 10 (35°40'48.6"N 139°28'22.3"E)



Higashimurayama – Site no 11 (35°44'55.8"N 139°27'16.5"E), Site no 12 (35°44'54.2"N 139°27'19.9"E), Site no 13 (35°44'52.4"N 139°27'25.1"E), Site no 14 (35°44'44.2"N 139°27'42.8"E), Site no 15 (35°44'47.4"N 139°27'35.2"E), Site no 16 (35°44'45.6"N 139°27'39.1"E), Site no 17 (35°44'46.3"N 139°27'28.7"E), Site no 18 (35°44'50.1"N 139°27'23.0"E) , Site no 19 (35°44'45.3"N 139°27'23.4"E) and Site no 20 (35°44'49.3"N 139°27'31.6"E)

Note for Appendix A

Map Source: Google Maps (2019)

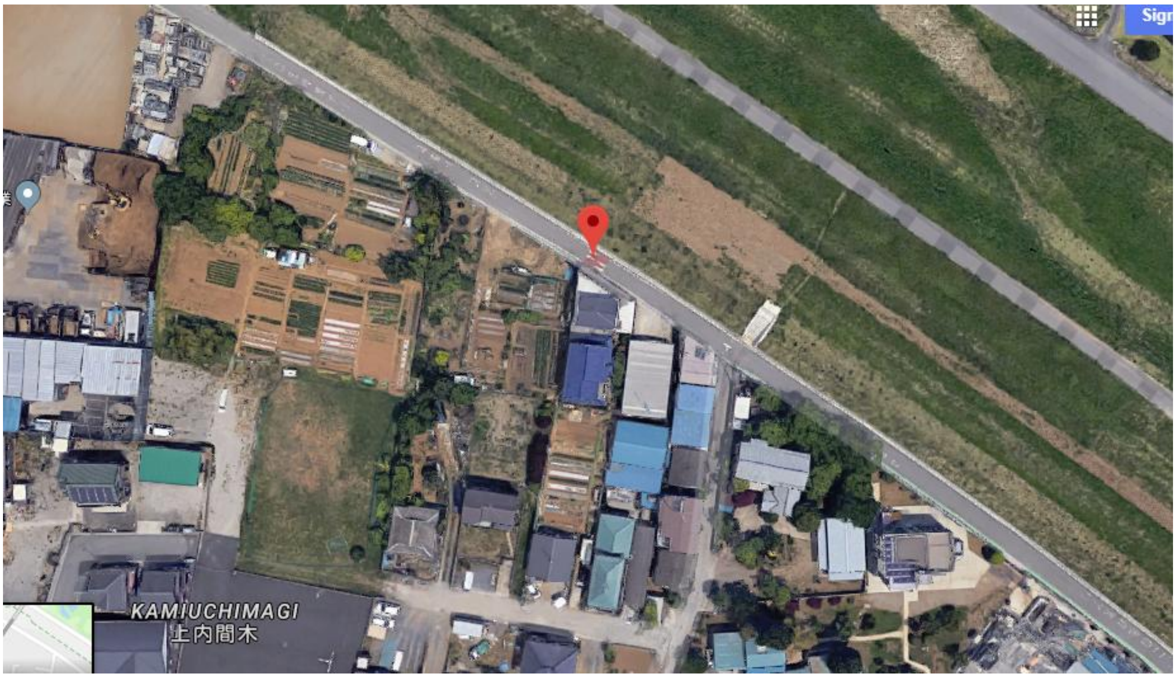
The number in the rectangle indicates Site No -

The red colored circle indicates Hump Position -

Total 20 site - 2 in Bunkyo
- 8 in Fuchu
- 10 in Higashimurayama

Asaka (Saitama Prefecture) – Hump (35°49'43.1"N 139°36'46.3"E)

https://www.google.com/maps/place/35%C2%B049'43.1%22N+139%C2%B036'46.3%22E/@35.8286245,139.6129436,119m/data=!3m1!1e3!4m14!1m7!3m6!1s0x6018e99b42bdc515:0x840d46de25832da5!2sAsaka,+Saitama!3b1!8m2!3d35.7971702!4d139.5936412!3m5!1s0x0:0x0!7e2!8m2!3d35.8286313!4d139.612865



Kita-Ageo (Saitama Prefecture) – Hump (35°58'37.1"N 139°34'10.8"E)

https://www.google.com/maps/place/35%C2%B058'37.1%22N+139%C2%B034'10.8%22E/@35.9768813,139.5696226,120m/data=!3m1!1e3!4m6!3m5!1s0x0:0x0!7e2!8m2!3d35.9769706!4d139.5696598

Miyoshi (Saitama Prefecture) – Hump (35°49'46.3"N 139°31'26.5"E)

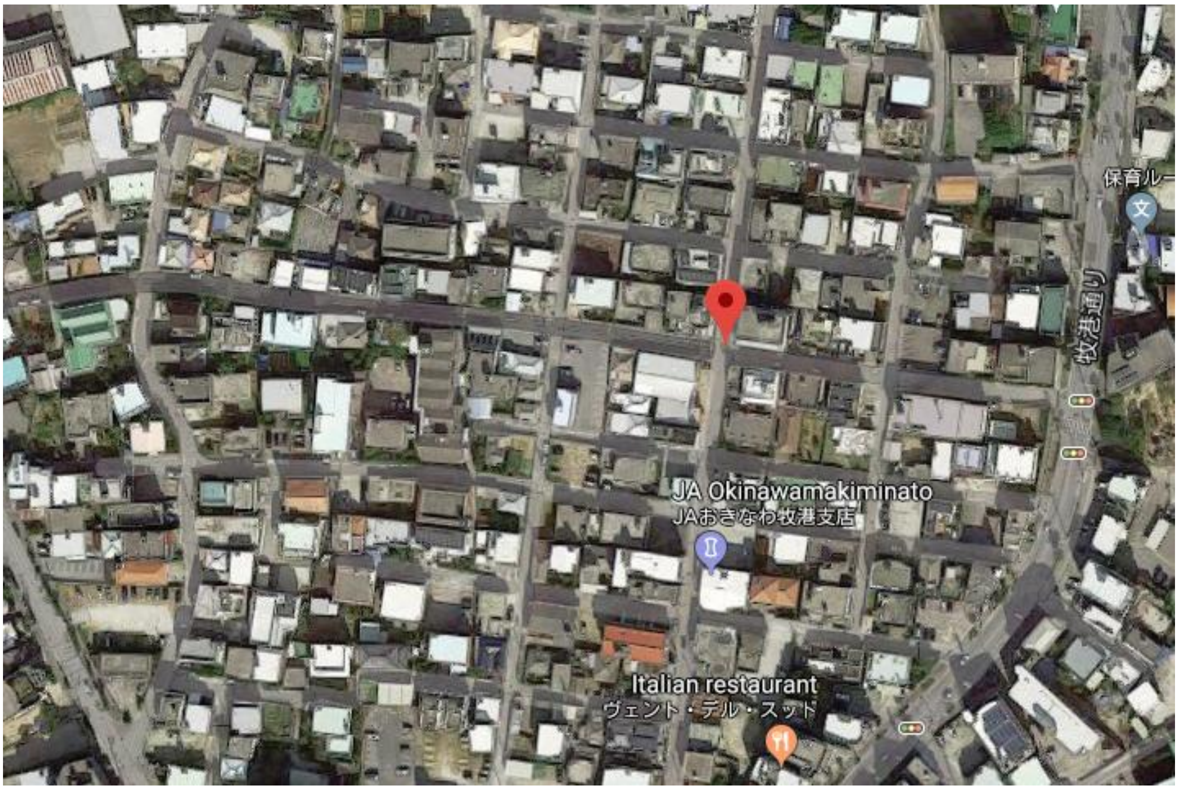
https://www.google.com/maps/@35.8295116,139.5239604,3a,75y,62.87h,82.29t/data=!3m6!1e1!3m4!1s5AnoZvPZgZWAf6NR_RXOuQ!2e0!7i16384!8i8192

Tsurugashima (Saitama Prefecture) – Hump (35°56'09.7"N 139°23'41.5"E)

https://www.google.com/maps/place/35%C2%B056'09.7%22N+139%C2%B023'41.5%22E/@35.9359064,139.3950618,143m/data=!3m1!1e3!4m14!1m7!3m6!1s0x6018d7b4a7ea7f0f:0xdfc129e22ca93d14!2sTsurugashima,+Saitama!3b1!8m2!3d35.9345047!4d139.3931269!3m5!1s0x0:0x0!7e2!8m2!3d35.9360357!4d139.3948675

Makiminato (Okinawa Prefecture) – Temporary Hump (26°15'47.6"N 127°43'22.8"E)

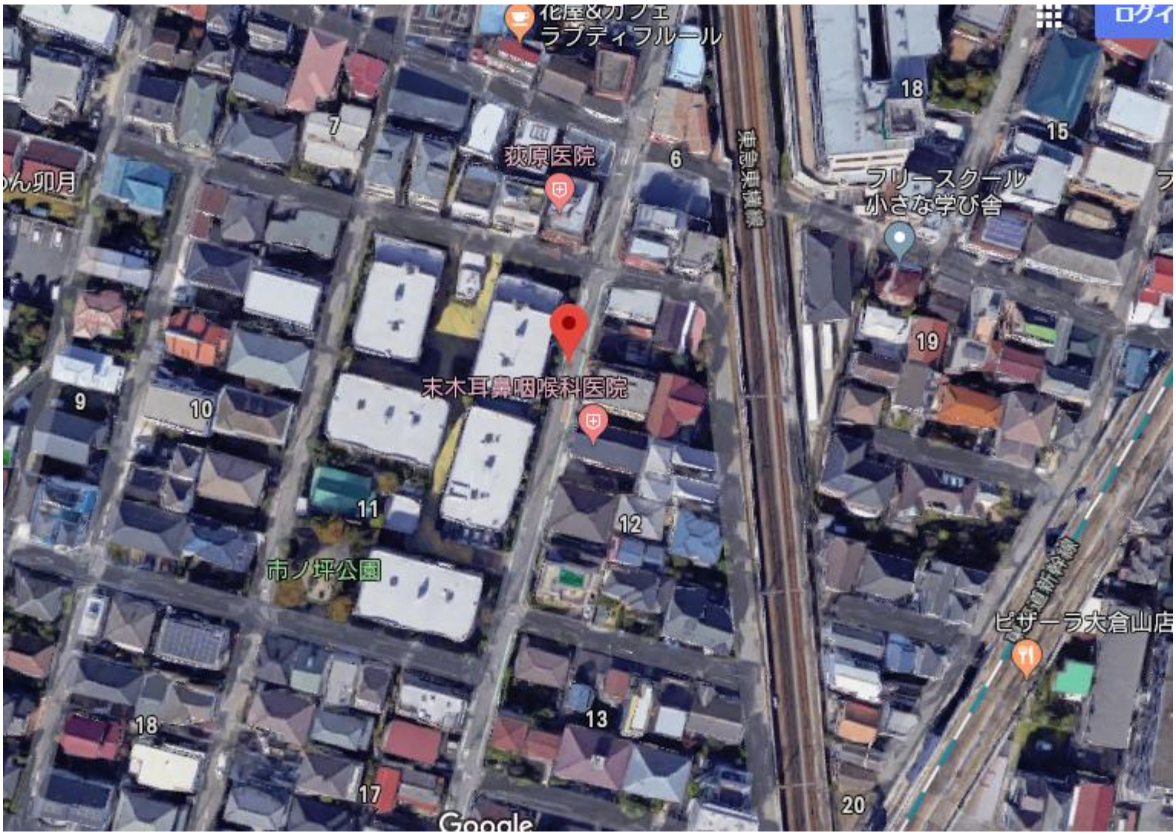
https://www.google.com/maps/place/26%C2%B015'47.6%22N+127%C2%B043'22.8%22E/@26.2630876,127.7224165,317m/data=!3m1!1e3!4m6!3m5!1s0x0:0x0!7e2!8m2!3d26.2632224!4d127.7229847



Nakanishi (Okinawa Prefecture) –Hump (26°14'57.7"N 127°42'24.0"E)

https://www.google.co.jp/maps/place/26%C2%B014'57.7%22N+127%C2%B042'24.0%22E/@26.2493588,127.7044579,632m/data=!3m2!1e3!4b1!4m13!1m6!3m5!1s0x34e56b99e5941617:0xbff0b00d3da4b7f7!2z5rWm5re75biC56uL5Luy6KW_5bCP5a2m5qCh!8m2!3d26.250147!4d127.7068571!3m5!1s0x0:0x0!7e2!8m2!3d26.2493537!4d127.7066521?hl=ja

Yokohama (Kanagawa Prefecture) – Temporary Hump (35°31'11.1"N 139°37'46.6"E)
https://www.google.co.jp/maps/place/35%C2%B031'11.1%22N+139%C2%B037'46.6%22E/@35.5197605,139.628829,203m/data=!3m2!1e3!4b1!4m13!1m6!3m5!1s0x60185f1ff5f5b6cf:0x5d022ca997dc5498!2z5aSn5YCJ5bGx6aeF!8m2!3d35.5218361!4d139.6298577!3m5!1s0x0:0x0!7e2!8m2!3d35.5197586!4d139.6296046?hl=ja



Nakayama (Kanagawa Prefecture) – Temporary Hump (35°30'52.6"N 139°32'50.3"E)
https://www.google.co.jp/maps/place/35%C2%B030'52.6%22N+139%C2%B032'50.3%22E/@35.5146081,139.5467665,143m/data=!3m2!1e3!4b1!4m6!3m5!1s0x0:0x0!7e2!8m2!3d35.5146071!4d139.5473152?hl=ja