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Analysing the Impact of Jaywalking Pedestrians on Mainstream Traffic Flow through Real-time Motion Trajectories

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Abstract: Growth of road users in urban areas results in consequential higher interactions between pedestrians and vehicles causing delays to mainstream traffic flow. The delay caused by random jaywalking pedestrians across the carriageway is substantial. The research was conducted to study the interaction between the vehicles and jaywalking pedestrians and thereby explore the impact on the mainstream traffic due to jaywalking pedestrians in terms of delay and speed reduction. The delay and speed reduction variations are influenced by the characteristics of the crossing pedestrians and the behaviour of on-coming vehicles. Both the movement of the vehicles and crossing pedestrians on the subject lane were tracked using tracking software. Two multiple linear regression models for the delay and speed reduction of mainstream traffic were developed for the consequential characteristics. The applicability of the proposed model for each vehicle and pedestrian characteristic has been determined and evaluated based on their level of significance. If other predictors are kept constant, the delay caused by three-wheelers, cars/vans/jeeps, and trucks/lorry buses is 0.39s, 0.78s and 1.17s, respectively, whilst the speed reduction accounts for 0.32ms^{-1}, 0.64ms^{-1}, and 0.96ms^{-1}, respectively.

Keywords: Delay model, Speed reduction model, Jaywalking pedestrian, Mainstream vehicles, Heterogeneous traffic

1. Introduction

Pedestrian-vehicle interaction is often observed on roads resulting in undesirable traffic congestions in the mainstream traffic flow when yielding for jaywalking [1]. The main objective of this research was to study the interaction between the jaywalking pedestrians and the subjected vehicle in mainstream traffic. Many previous studies have beencarried out to develop speed models to determine the delay. However, most of them have been conducted under homogeneous conditions. The methodologies developed under such studies may not be directly applied to developing countries where mostly heterogeneous traffic conditions exist. The study of influential pedestrian characteristics is vital as it is contingent on the driver yielding behaviour. Yielding to jaywalkers causes speed reduction and delay to the subjected vehicle on the traffic flow, resulting in a high sustained delay to the mainstream traffic. Therefore, this study is focused on developing regression models for the speed reduction and delay of the subjected vehicle on the mainstream in contrast to the governing pedestrian and vehicle characteristics.

2. Literature Review

Random jaywalking is influenced by various factors and many studies have been conducted taking demographic characteristics of jaywalkers that influence the gap acceptance behaviour. Kadali and Vedagiri [2] conducted a study considering age and gender. They found that neither age nor gender is critical in the gap acceptance behaviour. However, this result contradicts other studies, as Sun et al. [3] and Das et al. [4] showed that age and gender have a substantial effect on the gap acceptance behaviour. They also studied the pedestrian crossing patterns and found that pedestrians are more likely to cross in a staggered manner, especially on a divided road where there is a higher traffic density on the median lane. The delay in mainstream traffic from jaywalking pedestrians is not only influenced by pedestrian

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characteristics alone, but also due to vehicle characteristics and traffic characteristics [5]. Bassani et al. [6] found that an average speed reduction of 7.23 km/h is caused by the pedestrians sharing the right of way due to the absence of a sidewalk specifically on urban roads. Advani and Nisha [7] found that high volumes of pedestrians walking beside the roadway led to a lower speed on urban streets.
Shukla and Chandra [8] established a speed prediction model for urban roads that are having considerable pedestrian engagements along the carriageway and found that a 0.35 km/h speed reduction occurs to the mainstream traffic flow for each pedestrian walking beside the sideway. However, the speed reductions are influenced by both pedestrian characteristics and the behaviour of the on-coming vehicles [9]. Moreover, Varhelyi [10] found that the average speed reduction of the mainstream traffic flow is 2 km/hr when a single pedestrian is present and about to cross the road on one side. The speed reduction increases to an average of 5 km/hr when there are multiple pedestrians present and about to cross from both sides of the road. Thiessen et al. [11] found that pedestrian movements across the road cause an operating speed reduction of 2 km/hr.

The jaywalking pedestrians cause vehicle queues due to the delays caused in signalized intersections [12]. Nevertheless, there are some studies which explain traffic movement in contrast with empirical models or other adjustment factors. Silvano and Bang [13] conducted many studies about the speed characteristics on urban roads concerning the different factors that govern driver and pedestrian attributes. Hence a speed model was introduced, which is,

$$V_{average} = 48.7 - 0.011Y_1 - 0.015Y_2 \qquad ...(1)$$

where:

Y_1 = Vehicle volume on both directions (veh/h)

Y_2 = Pedestrian volume (ped/h/km)

Golakiya and Dhamaniya [14] conducted a study in heterogeneous traffic conditions and proposed a regression model to find a speed of a specific vehicle under the influence of other vehicles. This model emphasizes more the selected vehicular categorical speed given by:

$$V_j = a_0 - \sum\left(a_k \times \frac{n_i}{V_i}\right) - a_k^{\frac{n_{ped}}{V_j}} \qquad ...(2)$$

where:

V_j= Vehicle speed of j[th]type of vehicle (m/s)

V_i = Vehicle speed of i[th]type of vehicle (m/s)

a_0= Regression coefficient representing the free flow speed of vehicle type j

a_k = Regression coefficient relevant to the impact of density on the free flow speed of the j[th] vehicle category.

n_{ped} = Number of pedestrians

n_{ped} = Number of i[th]type of vehicles

However, it was observed that most of the previous studies have evaluated speed reduction and delay as values. The existing studies have also developed linear models to predict the speed of the mainstream traffic flow due to vehicle and pedestrian interaction. Additionally, the driving patterns influence vehicle acceleration and deceleration patterns [15]. As the speed behaviour is varying with mixed traffic conditions it is imperative to introduce a linear equation to model the speed reduction and delay by considering the governing vehicle and pedestrian characteristics in heterogeneous traffic conditions.

3. Methodology

3.1 Data Collection

Initially, the locations were selected considering the vehicle and pedestrian densities during peak and off-peak hours. Therefore, the data collection was done to have a complete dataset comprising the peak and off-peak vehicle and predestrian densities. Data were collected in Kiribathgoda, Sri Lanka. Figure 1 shows the aerial view of the selected site location.

Figure 1 - Aerial View of the Location

The considered road section is an A-class two-way, two-lane divided dual carriageway section with a center median. This road section has a clear center median without barriers for a length of 142m.Data collection was carried out on Tuesday and Saturday from 4.00 pm to 6.00 pm after considering the vehicle and pedestrian densities of the selected section. The average jaywalking frequency was observed as 40 pedestrians/hr. The considered mean speed was around 40km/hr which is the urban speed limit. The vehicle headway consideration was done so that a minimum headway of 10m was to be maintained. However, the vehicle speed and headway were of minor deviations from the considered values due to the vehicle density variations in upstream and downstream of the main traffic flow. The selected road section was a flexible pavement having a uniform surface and negligible undulations. It did not have any road humps, barriers or any potential disturbance for the subjected vehicles or pedestrians and did not have any curves or bent road sections.

3.2 Data Extraction

The data extraction was conducted in two stages while the final sample size accounted for 97 datasets. The first stage was the manual extraction whilst the second stage was the automated extraction. The pedestrian characteristics were extracted from the video camera mounted on the side of the road. Figure 2 shows jaywalking pedestrians observed in the study area.

Figure 2 – Jaywalking Pedestrians

Manual extraction of categorical variables of pedestrian-related characteristics such as gender, age, body type, carrying bags or not, attire, leg status, crossing pattern and group size were considered and the categorizations used are shown in Table 1.

Table 1 - Pedestrian Characteristics

Pedestrian Characteristic	Description
Gender	0 – Male 1 – Female
Age	0 – 45 Above 1 – 45 Below
Body type	0 – Skinny 1 – Fat
Bag	0 – No bag 1 – With bag
Leg status	0 – No limp 1 – With limp
Attire	0 – Trouser 1 – Skirt/Sarong
Crossing pattern	0 – Away 1 – Straight 2 – Towards
Group size	0 – One pedestrian 1 – Two pedestrians

Manual extraction of vehicle-related characteristics such as subjected lane and vehicle type are shown in Table 2. The extracted characteristics were categorized numerically as 0,1,2,3 considering the ascending delay order of each characteristic.

Table 2 - Vehicle-Related Characteristics

Vehicle Characteristic	Description
Subjected lane	0 – First lane (Near) 1 – Second lane (Far)
Vehicle type	0 – Motor Bike 1 – Three-Wheeler 2 – Car/Van/Jeep 3 – Truck/Lorry/Bus

Automated data extraction was carried out using the tracking software "TRACKER-4.11.0"as the interface shown in Figure 3. Pedestrian speed, the vehicle-pedestrian gap at the start, vehicle speed, vehicle acceleration, vehicle deceleration, distance travelled by the subject vehicle, idling time, and actual time for vehicle speed recovery were taken.

Figure 3 – Vehicle and Pedestrian Tracking

The speed variations due to jaywalking pedestrian movements were identified in three phases as speed reduction, idling and recovery as shown in Figure 4 whilst the parameter descriptions of each phase for V_1, V_2, V_3, V_4, t_1, t_2, t_3, t_4 and t_5 are summarized in Table 3.

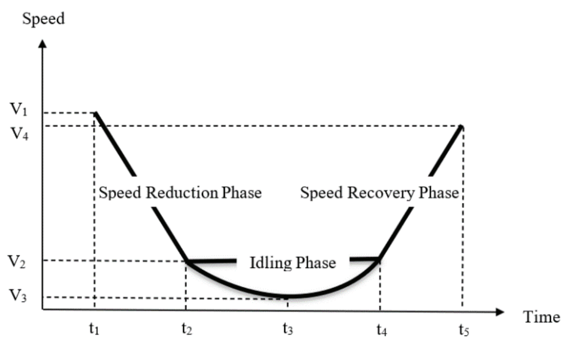

Figure 4 - Vehicle Speed Variation due to Jaywalking Movements

Table 3 - Parameter Description of Each Phase

Parameter	Description
V_1	Initial vehicle speed at the start of the speed drop / start of the speed reduction phase
V_2	Vehicle speed at the end of the speed reduction phase / start of the speed recovery phase / idling phase for a vehicle with having a constant speed at the idling phase
V_3	Vehicle speed at the end of the speed reduction phase / start of the speed recovery phase for a vehicle without having an idling phase
V_4	Vehicle speed at the end of the speed recovery phase / at the end
t_1	Time at the start of the speed drop / start of the speed reduction phase
t_2	Time at the end of speed reduction phase / start of idling phase for a vehicle having a constant speed at the idling phase
t_3	Time at the end of the speed reduction phase / start of the speed recovery phase for a vehicle without having an idling phase
t_4	Time at the end of idling phase / start of speed recovery phase for a vehicle having a constant speed at the idling phase
t_5	Time at the end of the speed recovery phase / at the end

The theoretical time for the vehicle speed variation was calculated using the recovery rates. Recovery rates were identified with three scenarios (1) complete recovery, (2) over recovery and (3) under recovery.

Complete recovery as shown in Figure 5 was identified when the constant speed travelled by the vehicle before the jaywalking impact happened is completely recovered and the recovery process of the speed drop is only influenced by the jaywalking scenario.

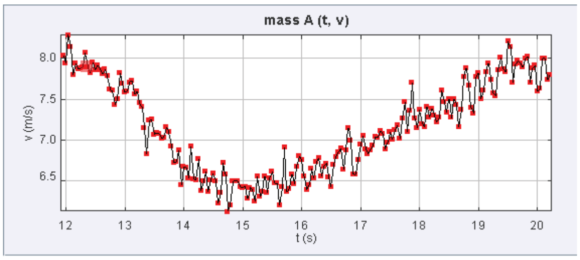

Figure 5 - Complete Recovery

Over recovery as shown in Figure 6 was identified when the constant speed travelled by the vehicle before the jaywalking impact happened is over recovered and the vehicle attains a higher speed than the drop at the start. The higher speed is attained due to the low vehicle density downstream. The recovery was considered a complete recovery and only the speed until the drop happened at the start was considered the influential jaywalking scenario.

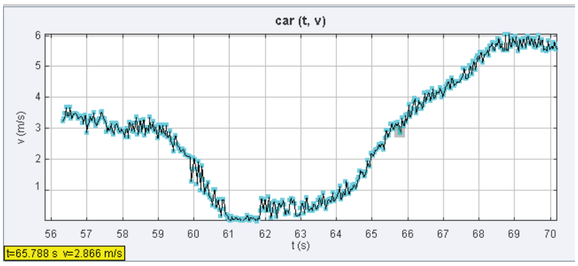

Figure 6 - Over Recovery

Under recovery as shown in Figure 7 was identified when the constant speed travelled by the vehicle before the jaywalking impact happened is not recovered and the vehicle attains a lower speed than the drop at the start. The lower speed is attained due to the higher vehicle density downstream. The recovery was considered until a constant speed is attained and the extraction was done considering the vehicle is decelerating.

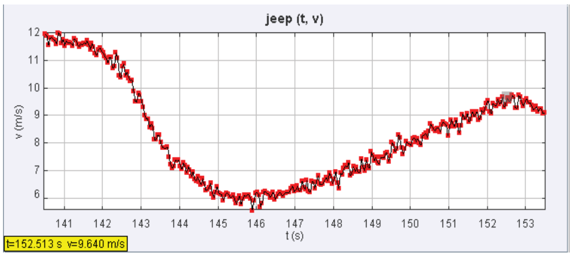

Figure 7 - Under Recovery

The data extraction was done by adhering to the conditions and limitations of the different vehicle speed recovery types. In addition, the field experiments discovered that the speed calculations from the software are of an accuracy of above 95%. Extracted data of traffic-related characteristics of the pedestrian and vehicle are summarized in Table 4.

Table 4 – Traffic Related Characteristics

Traffic Characteristic	Description
Deceleration $\frac{V_2 - V_1}{t_2 - t_1}$	Speed difference with respect to time in the speed reduction phase
Acceleration $\frac{V_4 - V_2}{t_5 - t_4}$	Speed difference with respect to time in the speed recovery phase
Distance travelled by the subjected vehicle (S)	The total distance travelled by the vehicle from the speed reduction phase to the speed recovery phase until the initial starting speed
Idling time ($t_4 - t_2$)	The time difference between the end of the speed reduction phase and the start of the speed recovery phase
Speed gap of the start and end ($V_1 - V_4$)	The speed difference between the initial speed in the speed reduction phase and the final speed in the speed recovery phase
Pedestrian speed at the start	Pedestrian speed at the initial speed of the vehicle in the speed reduction phase
Vehicle-pedestrian gap	The difference between the distance of the vehicle and the pedestrian at the initial speed of the vehicle speed in the speed reduction phase

The theoretical time calculation for complete and over recovery was obtained from Equation 3 and under recovery was obtained from Equation 4.

$$T = \frac{S}{V_1} \quad (3)$$

$$T = \sqrt{\frac{V_4 - V_1}{\left(\frac{V_4^2 - V_1^2}{2 \times S}\right)}} \quad \ldots (4)$$

The delay caused to the subjected vehicle on the mainstream by jaywalking was computed from Equation 5.

Delay = Actual time – Theoretical time ... (5)

The speed reduction of the subjected vehicle on the mainstream by jaywalking was computed from Equation 6.

Speed reduction = $V_1 - V_2$ (6)

3.3 Analysis Methods

Regression analysis was conducted to produce two linear models for the delay and speed reduction in the form of the multiple linear regression equation as shown in Equation 7.

$$Y = a_0 + a_1 X_1 + \cdots + a_n X_n \quad \ldots (7)$$

where,
Y = Dependent variable
X_1 = Independent variables from the pedestrian and vehicle characteristics
$a_0, a_1, \ldots a_n$ = Variable coefficients

The analysis was done in two processes, model fitting and model validation. The complete analysis was done using the R-STUDIO software. Model fitting was done for the training data set which was taken as 70% of the complete data set. Regression analysis was then performed with stepwise regression to identify the most significant variables in the delay and speed reduction models. The hypothesis is as below.

H_0 – There is no relationship between the dependent variable and the independent variable

H_1 – There is a relationship between the dependent variable and the independent variable

Model validation was performed for the test data set which was taken as 30% of the data set. Serial correlation was checked using the Durbin-Watson test. The hypothesis is as below.

H_0 – There is no correlation in the residuals

H_1 – There is a correlation in the residuals

Normality was checked using Anderson – Darling test. The hypothesis is as below.

H_0 – Data normally distributed

H_1 – Data not normally distributed

The correlation between the test data and the training data was checked so that there is minimal variation between the two data sets.

4. Results and Discussion

The backward stepwise regression was performed until all the individual variables attained a 95% confidence level of significance.

4.1 Delay Model

Results obtained from model fitting are shown in Table 5. The coefficient of each variable along with the individual significance and the relevant significance level is shown. It was observed that the vehicle speed and vehicle-pedestrian gap are highly significant towards the delay of the vehicle while the vehicle type, subjected lane, pedestrian age and speed are moderately significant towards the delay of the subjected vehicle. Nevertheless, the complete delay model indicates a p-value of 2.937×10^{-7} with a high R^2 value of 0.6388 which are satisfactory for practically obtained data. Thus, it was concluded that the model is acceptable as its relevant values are in the acceptable range.

Table 5 - Individual Variable Significance

Parameter	Estimate	p-value
Intercept	2.23649	0.00325
Subjected lane	1.16780	0.01074
Vehicle speed at the start	0.8421	1.93×10^{-5}
Vehicle speed at the end	-0.08583	9.7×10^{-6}
Veh-Ped gap at the vehicle speed drop	-0.04292	0.00545
Pedestrian speed at the start	-0.08948	0.03613
Age	1.16649	0.04395
Vehicle type	0.39856	0.03478

The proposed delay model introduces the absolute delay of the subjected vehicle due to jaywalking. This delay is interpreted in seconds per vehicle (s/veh) as the jaywalking impacts directly on the subjected vehicle. It was observed that the coefficient of the subjected lane is a positive value which can be interpreted that if the vehicle is travelling in the first lane and if the pedestrian is also at the start of the first lane and moving towards the second lane, then the delay is less. But if the vehicle is travelling in the second lane and the pedestrian crossing direction is from the first lane towards the second lane, then the delay of the vehicle is high. In the first event, the yielding effect is less whereas in the second event the yielding effect is high as the perception reaction time of the driver is high. A delay comparison of the subjected lane is shown in Table 6.

Table 6 - Delay Comparison of the Subjected Lane

Parameter	Event 1	Event 2
Vehicle position	On the first lane	On the second lane
Pedestrian position	At the start of the first lane	At the start of the first lane
Pedestrian crossing direction	From the first lane to the second lane	From the first lane to the second lane
Delay	LOW	HIGH

The coefficient of the vehicle speed at the start is a positive value, which means that if the speed of the subjected vehicle is high upstream then the delay caused due to jaywalking is also high as the speed drop could be potentially high and thereby the recovery is also potentially high. But, if the upstream vehicle speed is low then the speed drop and the recovery are comparatively low.

The coefficient obtained for the vehicle speed at the end was a negative value. This implies that if the vehicle attains a high speed of V_4 than V_1, then it is an over recovered or a complete recovered scenario, with a less delay occurrence from jaywalking. This is due to the influence of the acceleration event in the recovery phase. And if the end speed is low then it is less recovered, and the delay occurrence is high due to the deceleration event in the recovery phase.

The coefficient of the vehicle and pedestrian gap at the vehicle speed drop is a negative value inferring that, if the gap is low then the delay is high as there is a higher speed drop with small gaps. But if the gap is high then the speed drop is less, and the delay is less due to the yielding effect and the perception reaction of the driver.

The coefficient of the pedestrian speed at the start of the vehicle speed drop is a negative value, implying that if the pedestrian crosses the road at a high speed, then the speed drop of the vehicle is low and if the pedestrian crosses the road with a lower speed, then the vehicle speed drop and the recovery is high due to the yielding effect and the perception reaction of the driver.

The coefficient of the age is a high positive value which implies that if the age of the pedestrian is high the yielding by the driver is high which causes a higher delay. If other predictors are kept constant, the jaywalking pedestrians aged 45 and above cause a delay of 1.16 s.

The coefficient of the vehicle type is a positive value which suggests that for smaller vehicles such as bikes and three-wheelers the delay caused is less and for heavy vehicles, it is comparatively high. If other predictors are kept constant, the three-wheelers cause a delay of 0.39s while cars/vans/jeeps, and trucks/lorries buses cause a delay of 0.78 s and 1.17 s, respectively. The parameter significance reveals that delay is influenced by driver yielding rates and pedestrian critical gaps [16]. Model validation results of autocorrelation and normality are shown in Table 7. Therefore, there is no serial correlation between the residuals and the residuals are normally distributed. The correlation coefficient was obtained as 0.45 which is an acceptable value for practically tested data.

Table 7 - Model Validation Results

Name of the test	Result	
Durbin-Watson Autocorrelation test	DW value = 1.716 (Between 1.5 and 2.5)	p-value = 0.0888 > 0.05
Anderson-Darling Normality test	AD value = 0.1624	p-value = 0.9451 > 0.05

4.2 Speed Reduction Model

It was observed that the vehicle speed and vehicle-pedestrian gap are highly significant towards the speed reduction of the vehicle while the vehicle type, subjected lane, pedestrian age and speed are moderately significant towards the speed reduction of the subjected vehicle. Nevertheless, the complete speed reduction model indicates a p-value of 2.2×10^{-16} with a high R^2 value of 0.8759 which are satisfactory for practically obtained data. Thus, it was concluded that the model is acceptable as its relevant values are in the acceptable range. Results obtained from model fitting are shown in Table 8.

Table 8 - Individual Coefficient Results

Parameter	Estimate	p-value
Intercept	-0.92267	0.09247
Acceleration	2.00213	$3.10\text{x}10^{-5}$
Deceleration	-0.61438	0.04272
Distance travelled by the subjected vehicle	0.02769	0.00221
Idling time	-0.71932	0.00044
Pedestrian speed at the start of the vehicle speed drop	-0.63098	0.00128
Speed gap of the start and end	1.33752	$2.24\text{x}10^{-11}$
Subjected lane	0.60614	0.02915
Vehicle type	0.31786	0.01509

The proposed speed reduction model introduces the absolute speed reduction of the subjected vehicle. This speed reduction is interpreted in meters per second (m/s) as the jaywalking impacts directly on the subjected vehicle. The coefficient for acceleration in the speed reduction model was obtained as 2.00213, expressing it as a very high value, comparatively. If the acceleration in the speed recovery phase is high, then the speed reduction is comparatively high. Therefore, high-speed drops result in aggressive acceleration patterns as the drivers tend to attain the initial travelling speed in a short period.

The deceleration coefficient was obtained as -0.61438 which can be implied as, with increasing decelerations the speed reduction is high. Sudden deceleration patterns cause a high-speed reduction. Therefore, high-yielding incidents cause high-speed reductions which also increase the possibility of an accident. These impact both pedestrian and vehicle user safety. As the total distance in the speed reduction and recovery phase was considered, the positive obtained coefficient implies that with higher distances the speed reduction is high. Therefore, if the total vehicle speed graph area is high then the speed reduction is high.

Idling time depends on many factors. However, higher idling time results in lower speed reductions as the perception distance increases. Higher perception distance results in lower yielding, which assists the driver to align with a lower and smooth speed reduction and recovering phase. Idling time is also a highly significant parameter in the speed reduction model. The coefficient of the pedestrian speed at the start of the vehicle speed drop is a negative value which can be interpreted that, if the pedestrian crosses the road at a high speed, then the speed drop of the vehicle is low, and if the pedestrian crosses the road with a lower speed then the vehicle speed drops and the recovery is high due to the yielding effect and the perception reaction of the driver.

The speed gap between the starting and end points was considered because of various speed recovery patterns. However, the complete recovered and over recovered patterns were considered as zero speed gaps due to the completion of the initial speed drop recovery. Yet the under-recovered pattern was considered to have a positive speed drop as there is a gap between the starting and end speeds. Therefore, it was observed that under-recovered speeds result in comparatively high-speed reductions.

It was observed that the coefficient of the subjected lane is 0.60614 which can be interpreted that if the vehicle is travelling in the first lane and if the pedestrian is also at the start of the first lane and moving towards the second lane then the speed reduction is less. But if the vehicle is travelling in the second lane and the pedestrian crossing direction is from the first lane towards the second lane then the speed reduction of the vehicle is high. This difference due to the vehicle travelling lane happened because of the yielding effect of the driver of the vehicle. In the first event, the yielding effect is less, causing a lower speed reduction whereas in the second event the yielding effect is high as the perception reaction time of the driver is high. The coefficient of the vehicle type is a positive value which implies that for smaller vehicles, such as bikes and three-wheelers, the speed reduction caused is less, and for heavy vehicles it is comparatively high. Model validation results of autocorrelation and normality are shown in Table 9.

Table 9 - Model Validation Results

Name of the test	**Result**	
Durbin-Watson Autocorrelation test	DW value = 1.567 (Between 1.5 and 2.5)	p-value = 0.0888 > 0.05
Anderson-Darling Normality test	AD value = 0.69203	p-value = 0.0666 > 0.05

Therefore, there is no serial correlation between the residuals and the residuals are normally distributed. The correlation coefficient was obtained as 0.77 which is acceptable for the obtained model. So, the model was completely validated thereby satisfying all the relevant statistical checks and assumptions in regression analysis.

5. Conclusions

In this research, the regression modelling technique was used to introduce a delay model and a speed reduction model for the interaction occurring with the subjected vehicle in the mainstream traffic due to the pedestrians crossing illegally in urban and suburban areas on road sections. The collective pedestrian and vehicle characteristics in a jaywalking situation influencing the speed variations were identified and analysed in this study.

The delay of the subjected vehicle on the mainstream mainly depends on the variables such as the subjected lane, vehicle speed at the start, after the recovery of the speed drop, vehicle and pedestrian gap at the start of the vehicle speed drop, age of the pedestrian and the vehicle type. The speed reduction of the subjected vehicle on the mainstream mainly depends on the variables such as acceleration, deceleration, distance travelled by the subjected vehicle, idling time, pedestrian speed at the start of the vehicle speed drop, subjected lane, and the vehicle type.

This study is one of the first studies that has been done considering the vehicle and pedestrian characteristics such as acceleration, deceleration, speed, and gaps while introducing delay and speed reduction models in heterogeneous traffic conditions. Accordingly, this study will be useful to estimate the collective speed reduction and the delay from such vehicle and pedestrian characteristics under different events. Moreover, the results of the study will be useful to identify the speed variations by excessive jaywalking pedestrians in identified zones and to implement potential developments to the road infrastructure to enhance the level of service and the safety of pedestrians.

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