Simulating Hazardous Traffic Condition for Urban Expressways - A Micro-Simulation Approach

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ABSTRACT

Micro-simulation approach is a profound tool used by researchers to determine and analyze traffic characteristics. Micro-simulation approach gives access to car following as well as lane changing behavior of individual vehicle and allows analyzing their interactions by changing the parameters. CUBE Dynasim is a micro-simulation software developed by CITILABS which was used in this study. In CUBE Dynasim the normal traffic condition was created by using aggregated flow data obtained from Route 3 and Route 4 of Tokyo Metropolitan Expressway. The value of the parameters were altered to create hazardous traffic flow condition. In this study procedure to create a micro-simulation model is discussed in detail.Best possible result was obtained by changing the values of car-following maximum threshold and mean of threshold value for car following rules. Again, in case of lane changing behavior changing of heavy vehicle threshold, light vehicle average time, light vehicle minimum time, light vehicle maximum time, light vehicle standard deviation, light vehicle minimum distance, heavy vehicle average time, heavy vehicle minimum time, heavy vehicle maximum time, heavy vehicle standard deviation, heavy vehicle minimum distance reflected best result.

Keywords: *Micro-simulation; Hazardous Traffic Condition; Car-following; Lane Changing; Pro-active Road Safety*

1. INTRODUCTION

Objectives of urban expressways are to reduce travel time, mainly during the peak hour connecting major traffic attractions and productions. They are by design highly access controlled and can be quite expensive to construct. Urban expressways in general have fewer numbers of lanes than freeways or surface roads. In many cases they are privately operated as well. Hence, when there is a crash occurring on the urban expressways, the consequences are high. A crash during peak hour on an urban expressway can heavily impact the travel time, which was the primary objective of building such structures. At the same time, it results in heavy loss of revenue and low accessibility can make rescue activity quite challenging as well.

Remarkable developments in the field of Intelligent Transportation System (ITS), is seen in past two decades. These have promoted several studies on improving safety aspects of access controlled roads. Now a day, many of the expressways in the developed world are instrumented which are generating a substantial amount of data on the current traffic condition in real-time. This has opened the door to monitor traffic condition closely and identify any anomaly that can evolve into a hazardous traffic condition elevating the probability to make driving errors. This one and a half decade old field in transportation deals with predicting crash probability in real-time and the resulting models is called real-time crash prediction models.

Speed variation was a prime variable on likelihood of occurrence of crash which was developed based on real data (Oh et al. 2001). By establishing relationships between coefficient of variation in speed, traffic density and speed difference to determine likelihood of crash occurrence, a log linear model for freeway and ramp was developed by Lee et al. (2003). Separate real-time crash prediction model was developed by Hossain and Muromachi, (2011). Clustering analysis to establish connection between different traffic states and crash risks on freeways was used by Xu et al. (2012). Crash prediction models were also developed using crash reports, real-time traffic and weather data (Yu and Abdel-Aty 2014).

For a proactive road safety management system, after predicting crashes, it is important to be able to identify how to bring the traffic condition back to normal. Several studies have shown that it is possible to bring the traffic condition back to normal by the implementation of different interventions.

Variable Message Signs have been incorporated in many metropolitan cities in the world (Van Eeden et al., 1996) in the hope that the information provided by these signs will alter drivers' behaviour in appositive manner. Louma and Rama (2001) studied the comprehension of pictograms for VMS conducted on European drivers, demonstrated how difficult it is to find images which are readily understood.

The relationship between speed and accidents is a complex one. Worldwide 5 to 15% accidents occur due to over speed. Anderson and Nilsson (1997) reports that the reduction of speed by 1 mile/h (1.6 km/h) reduces the casualties by 5% and reduction of mean speed by 10% results in a reduction in fatalities by 40%. Finch et al. (1994) suggests that an increase in mean speed by 2 to 4 miles/h (approximately 3 to 6 km/h) results in an increase in fatalities by 19 to 34%. Variable speed limits are commonly used with variable message signs in order to reduce the speed of vehicles to relieve congestion or warn of an unseen danger downstream (Gayah et al., 2006). VSL are used to increase average headways and reduce variances in speed (Borrough, 1997; Ha et al., 2003; Pilli-Sivola, 2004). This translates into fewer crashes (Smulders, 1990). Borrough (1997) found that the use of VSL and strong enforcement (video cameras) greatly reduce the number of crashes (28% over 18 months). The effect was attributed to not only a smoothing of traffic conditions through longer following distances, but also through reducing the number of lane changes during congestion (Borrough, 1997). Lee et al. (2004) used VSL to try and reduce crash potentials. Abdel-Aty et al. (2006) used a longer stretch of freeway from I-4 in Orlando to test the effect of VSL. Gayah et al.(2006) showed in their study that VSL had little to no effect on the crash risk index during the low-speed condition. This is most likely caused by the fact that during the low-speed scenario vehicles are travelling at congestion well below posted speed limit and, therefore, the change in speed limit on the roadway will not effectively change the speed the vehicles are travelling at.

The objective of ramp metering is to reduce delay and maintain capacity flow on a freeway by regulating access of ramp traffic to the mainline. Empirical studies have shown that ramp metering reduces turbulence in the merge zone, reduces variance in speed distributions, and thereby improves traffic safety i.e. reduces sideswipe and rear-end crashes (Lee et al., 2006). Ramp metering is used to reduce congestion by limiting the number of vehicles entering a freeway at a given time to avoid bottlenecks that typically occur at freeway on-ramps (Gayah et al., 2006). Empirical studies suggested that ramp metering reduces crash rate (Cambridge Systematics, 2001) and more specifically rear-end and sideswipe crashes in the freeway mainline (Cleavenger and Upchurch, 1999). Many studies in North America and Europe have assessed the benefits of ramp metering quantitatively through field tests and simulation experiments. Thill et al. (2004) defined safety benefits of ramp metering as a decrease in crash frequency at the merging of ramp and freeway lanes from the baseline number of crashes. Currently, ramp metering is used throughout the United States in California, Minnesota and New York, as well as many countries throughout Europe (Gayah et al., 2006).

Considering these opportunities, some new studies are now taking place to evaluate the effectiveness of these road safety improvement solutions in real-time, when coupled with real-time crash prediction models. These studies take various traffic flow variables as input and from that apply various traffic interventions to bring the hazardous traffic conditions back to normal. As due to safety reasons these studies cannot be conducted in real life, researchers opted for either microscopic traffic simulation (Lee et al., 2006; Abdel-Aty et al., 2006, 2007, 2008) or driving simulator (Lee and Abdel-Aty, 2008) based approaches. The recommended countermeasures so far have been posting warning message (Lee and Abdel-Aty, 2008), variable speed limits (Abdel-Aty et al., 2006, 2008; Lee and Abdel-Aty, 2008) and ramp metering (Lee et al., 2006;Abdel-Aty et al., 2007),which have proven track record as effective solutions as discussed in the aforementioned subsections.

Simulation based approach are favoured because those could evaluate different scenarios as well as could reflect accuracies. For studies involving crash data it is not possible to recreate the environment in real field. That's why simulation based studies have been the key focus of the researchers. Methods like using a driving simulator or microscopic simulator are the prime method of such studies.

The use of driving simulator is not incorporated in this study because it would involve a lot of time as well as it would not be cost effective. Although it is to be noted that driving simulator could capture individual driving behaviour at a greater depth. But again it will depend much on the respondents. So in this study a micro-simulation based approach was chosen. CUBE Dynasim was used as the micro-simulation software.

In general, micro-simulation models are built to replicate normal traffic behaviour. But for road safety related studies it is important to know how to simulate hazardous traffic condition. So this study is focused on identifying and extracting hazardous traffic conditions from matching detector and crash database along with calibrating car-following and lane changing models to reproduce the hazardous traffic condition in a micro-simulation environment.

2. METHODOLOGY

2.1 Study area and the data

It is necessary to select such an area where it is possible to observe substantial amount of crash as well as means to collect crash data along with high resolution traffic flow data. High accuracy is also needed.

The data used in this study was collected from two parts of the Tokyo metropolitan expressways. The first one is Shibuya and the other one is Shinjuku 4 expressways. They were collected for a period of months from May to August on the year of 2014. The total length of the two expressways are 25.4 km. Shibuya Route (also known as the Route 3) is one of the radial routes of the expressway system in the Tokyo area. Route 3 runs southwest from Tanimachi Junction (with the Inner Circular route) in Minato-ku and runs for 12 kilometers through Shibuya-ku, Meguro-ku, and Setagaya-ku. The Route 3 designation ends at the Yoga Rampway (Tokyo Interchange) and the expressway continues as the intercity Tomei Expressway to Nagoya. Whereas, Route 4 (also known as the Shinjuku Route) is another radial routes of the Expressway system in the Tokyo area. It runs west from Miyakezaka Junction (with the Inner Circular Route) in Chiyoda-ku and runs for 13.5 kilometers through Shinjuku-ku, Shibuya-ku, and Suginami-ku. The Route 4 designation ends at the Takaido Interchange and the expressway continues as the intercity Chūō Expressway to Nagoya via Yamanashi and Nagano Prefacture.

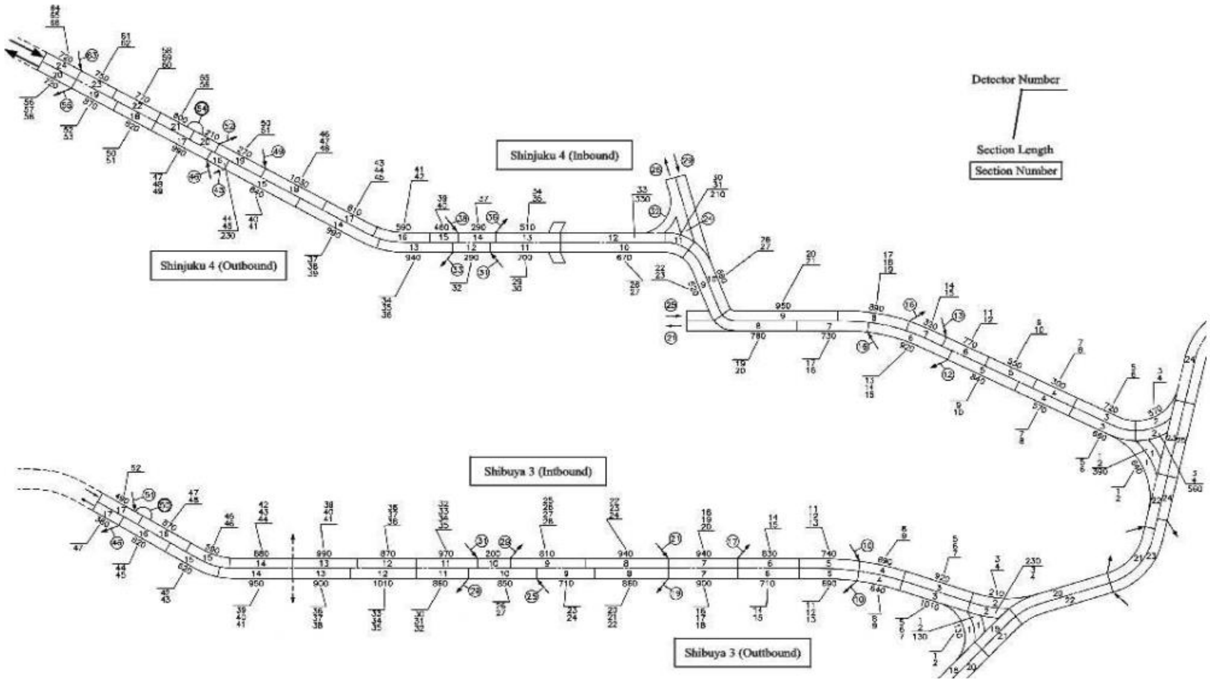

Figure 1: Schematic diagram of Route 3 and 4 of Tokyo Metropolitan Expressways (diagram not drawn to scale)
Source: provided by Tokyo Metropolitan Expressway Company Limited

A total no. of 24 ramps are present in the selected study area and approximately a total of 210 loop detectors were established there. A total 610 crashes were observed during the study period. Three classes of data were collected. These are detector data, crash data and road geometry data. The parameters set for collecting detector data were speed, flow, occupancy, number of heavy vehicles for each lane and ramps. Date, time, location, vehicles involved, types, lane were the parameters for collecting crash data. Road geometry data focused on location of ramps, position of detectors, section length.

2.2 Experimental setup

Data are preserved for each detector for every eight mili-seconds in Tokyo Metropolitan Expressways. Data is also stored for each lane covering information on speed, flow, occupancy and no. of heavy vehicles. Data for every one minute for each detector were aggregated and provided for the purpose of this study. Crash data including information on date, time, location, vehicles involved and types of lane were also added.

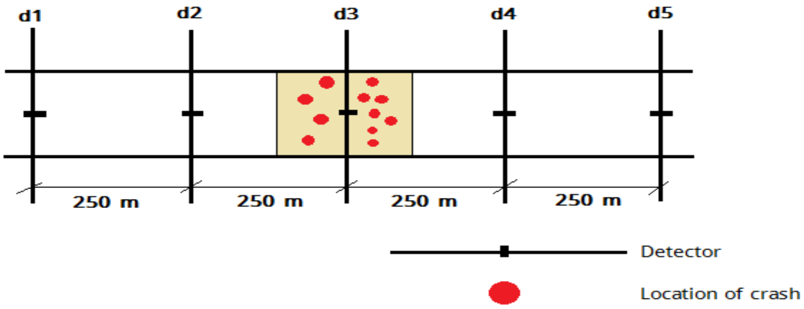

Figure 2: Position of detector and location of crash

The experimental setup was made as shown in the figure 2. Each crash points were associated with its corresponding 250meter section. For every section two upstream detectors, two downstream detectors and the detector within the section were identified. Two traffic conditions were identified hazardous traffic condition and normal traffic condition. For hazardous traffic condition (D_H^{ij}) 1 minute aggregated data for all lanes before i (i=1, 2, 3, 4, 5) minutes crash at j (upstream or downstream) junction were collected. On the other hand, for normal traffic random sampling of 1-minute aggregated data from any timeslot where no crash took place before or after that time period. The data collected from the detectors were then sorted and organized so that it can be easily incorporated in analysis. Each crash was given a single identification no. and speed, flow, occupancy data for 5 detectors as mentioned in the next segment was sorted.

2.3 Data Preparation

As it was mentioned, a total 210 detectors are placed in the two routes, when both directions are considered. The primary task was to identify nearest detector, upstream detector and downstream detector for each crash point, a sample of which is shown in table 1.

Table 1: Crash data with unique ID and detector located near crash (sample)

Crash Id	**Date**	**Time**	**Day of week**	**Kilo-meters**	**Segment-s**	**Kilo post**	**D2D**	**D1D**	**D0**	**D1U**	**D2U**
481	4/30	06:46 pm	Wed	0	1	0.10	04	01	03	-	-
482	6/14	11:24 am	Sat			0.20	02	04	01	03	-
483	3/27	07:03 pm	Thurs			0.20	02	04	01	03	-
484	3/21	07:13 pm	Fri		2	0.30	02	04	01	03	-
485	7/7	11:15 am	Mon			0.30	02	04	01	03	-
486	3/30	07:54 pm	Sun		3	0.60	06	05	02	04	01
487	5/23	09:53 am	Fri			0.60	06	05	02	04	01
488	6/7	02:02 am	Sat	1	1	1.00	08	07	06	05	02

Here, D0 = Detector in the segment
D1D = First detector in the downstream
D2D = Second detector in the downstream
D1U = First detector in the upstream
D2U = Second detector in the upstream

Then it was needed to sort the data from all detector and combine them together so that it can be easily found and used during the course if this study. A sample of such work is shown in table 2.

Table 2: Crash data with unique ID and detector located near crash (sample)

Crash ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Date	6/7	6/10	6/29	3/21	8/15	8/18	6/29	3/13	8/7	8/27	8/28
Time	21:25	02:28	03:26	17:47	08:01	16:22	11:06	21:25	17:58	19:47	9:14
Kilo post	0.00	0.10	0.10	0.10	0.10	0.10	0.20	0.20	0.20	0.20	0.20
D1D_f_15	4	13	3	2	18	7	28	11	21	4	24
D1D_f_14	10	8	2	2	23	16	22	12	9	18	13
D1D_f_13	13	4	1	2	27	19	21	9	18	13	23
D1D_f_12	12	8	3	5	20	16	29	9	18	13	26
D1D_f_11	10	8	2	2	19	17	25	14	15	10	22
D1D_f_10	10	11	7	1	20	22	19	4	20	14	19
D1D_f_9	11	13	2	2	20	8	25	16	15	16	19
D1D_f_8	14	18	0	1	23	19	23	15	17	19	23
D1D_f_7	12	4	5	4	22	19	22	7	12	22	13

Here, D1D_f_t = flow data of detector at time t minutes before crash

2.4 Microscopic Traffic Simulation with CUBE Dynasim

In microscopic traffic simulation it is possible to model traffic behavior by calibrating car following and lane changing parameters. The methodology followed to calibrate these parameters are discussed in detail in the following sections.

2.4.1 Car Following Rules

There are two car following rules followed in CUBE Dynasim. First one is MGA, which is acronym for General Motors Ahmed and the other one is PLP7. The car following depends on speed, space headway, density, relative speed, free-flow acceleration, headway threshold and reaction time distribution. Most algorithm used in MGA was taken from a paper written by Kazi Iftekhar Ahmed in 1999. Whereas, PLP7 is a simple acceleration model. In it only three parameters are considered. This is very useful in modelling congestion in urban traffic. The acceleration of vehicle 2 which follows vehicle 1 is determined by the speed and the distance from the vehicle which precedes it according to the formula:

$$A2^*(t+0.25) = \alpha^* [V1(t) - V2(t)] + \beta^* [X1(t) - X2(t) - \tau^* V2(t) - L] \qquad (1)$$

Here, A1 = Acceleration of vehicle 1
A2 = Acceleration of vehicle 2
t = Time at any instant
V1 = Velocity of vehicle 1
V2 = Velocity of vehicle 2
X1 = Position of vehicle 1
X2 = Position of vehicle 2

Table 3: Value of α, β, τ

A1(t)	**A**	**B**	**T**
< -0.6 m/s2	0.7	0.03	1.82
[-0.6 ; 0.6]	1.1	0.2	0.52
> 0.6 m/s2	0.36	0.03	1.82

2.4.2 Lane Changing Parameters

In CUBE Dynasim two types of situations can lead to a lane change. The first one is a lane change imposed by the path the vehicle takes to reach its destination, conditioned by "Insertion gaps" and a the other one is a lane change due to the vehicle's behavior usually conditioned by "Behavior associated with lane satisfaction". Insertion gaps determine whether the vehicle will be able to change lanes depending on the traffic in its target lane. Behavior associated with lane satisfaction can be of two sorts. First one is current lane satisfaction, which determines whether or not a vehicle is satisfied with the traffic conditions in the current lane. Whereas, target lane satisfaction determines whether a vehicle wants to change lanes depending on the traffic in adjacent lanes.

A vehicle that wants or needs to change lanes must make sure, in terms of safety, that the vehicles in front and behind in its target lane are at a sufficient distance from its front and rear bumpers. This is done using lag and lead insertion gaps. In CUBE Dynasim the calculated acceptable gap distance depend on the instant speed of the vehicle V(t), the speed of the vehicle in the target lane V_C(t). The minimum acceptable gap for changing lanes is determined by following formula (Dynasim Manual, 2014):

$$G(t) = \exp(C_1 + C_2 Max(0, V_c(t) - V(t))) + C_3 Min(0, V_c(t) - V(t))) + C_4 n + N(0, C_5^2)) \tag{2}$$

Here, C_1 = Constant.

C_2 = Positive speed differences (*dv+*), i.e. the difference between the instant speed of the vehicle in the current lane V(t) and the speed of the vehicle in the target lane V_c(t)

C_3 = negative speed differences parameter (*dv-*), i.e. the difference between the instant speed of the vehicle in the current lane V(t) and the speed of the vehicle in the target lane V_c(t)

C_4 = Aggressiveness parameter associated with a random selection n which serves to reflect different types of driving

C_5 = Standard deviation of the normal distribution centered on 0

It is very important to note that in CUBE Dynasim a lane change not imposed by a vehicle's destination depends on the lane satisfaction in the current and adjacent lanes. The behavior assigned to a lane in a trajectory will define the conditions in which the vehicles concerned will want to move to the target lane. In fact, if a vehicle does not satisfy the lane satisfaction condition on its current lane, but satisfies the condition on the target lane it will change lanes. Current lane satisfaction depends on the instant speed of the vehicle V(t) and the desired maximum speed of the vehicle V_1(t). The probability that a vehicle is not satisfied in its current lane is as follows (Dynasim Manual, 2014) :

$$P(t) = \frac{1}{1+e^{(C_1+C_2(V(t)-V_1(t))+C_3\delta_{PL}+C_4\delta_{PA})}} \tag{3}$$

Here, C_1 : Constant.

C_2 : A *dV* maximum parameter relative to the difference between the instant speed of the vehicle V (t) and the desired maximum speed of the vehicle V_1(t)

C_3 : An *HV* penalty parameter, used for vehicles whose length in m exceeds the threshold specified in the *Heavy thr* field

C_4 : A tailgate parameter (TG) relative to the distance between the vehicle and the vehicle directly behind it, used for vehicles whose speed is greater than the tailgate speed threshold specified in the *Speed thr* tail field

δ_{PL}= 1, If the length of the vehicle considered is greater than the value specified in the *Heavy Thr* field
δ_{PA}= 0, if the distance between the vehicle considered and the vehicle directly behind it is less than 10

Target lane satisfaction depends on the instant speed of the vehicle V(t), the maximum desired speed of the vehicle V_1 (t), the speed of the lag vehicle V_P (t), in the current lane the speed of the lag vehicle and of the lead vehicle in the target lane V_CP (t) and V_CS (t) respectively. The probability that a vehicle will want to change to a target lane is as follows (Dynasim Manual, 2014):

$$P(t) = \frac{1}{1+e^{(C_1+C_2\left(V_P(t)-V_1(t)\right))+C_3\ (V_{CP}(t)-V_1(t))+C_4(V_{CS}(t)-V_1(t))}} \tag{4}$$

Here, C_1: Constant
C_2: A *Dvfront* parameter relative to the difference between the speed the vehicle wants to reach V_1(t) and that of the vehicle in front V_P(t)
C_3: A Dv lead parameter relative to the difference between the speed the vehicle wants to reach V_1(t) and that of the vehicle in front in the adjacent laneV_{CP} (t)
C_4: A Dvlag parameter relative to the difference between the speed vehicle V (t) and that of the vehicle behind in the adjacent laneV_{CS} (t)

3. ANALYSIS AND RESULTS

This section reflects upon how to build a model in CUBE Dynasim step by step as well as how to calibrate the parameters to find out the expected flow-occupancy relationship.

3.1 Importing Map

The first step in modelling with CUBE Dynasim is to select and input the map in the software. The map could be in two formats, vector maps with DXF format and bitmaps in BMP, JPEG and GIF formats.

3.2 Drawing Network

In CUBE Dynasim network are drawn with handles and trajectories. Handles are defined by its position, its orientation and its number of attachment points. On the other hand, a trajectory is defined between two different handles. It can link one or more attachment points on the handles. A single lane is modelled by a trajectory that links a single attachment point on each handle. In certain conditions, the vehicles can change lanes depending on their behaviour, or to reach their destination**.**

3.3 Network and Flow Scenarios

The first step to take in defining a network scenario is to make a layer. Usually the very first layer is defined as Base. After a layer is created the next step to take is to define the network scenario. In the new network the created layer, input maps are selected. In CUBE Dynasim different types of flow scenarios are also included. These are aggregate, generator, assignment, estimation, export-import, sub-network etc. and for the purpose of this study aggregate flow value of 15 minutes was introduced as input.

3.4 Driving Behaviour

In microscopic traffic simulation individual driving behaviour is influenced by car following and lane changing parameters. As a detail discussion of car following and lane changing is done in the methodology section, in this section only the parameters which were changed from default value to obtain the hazardous traffic condition will be shown. In table 4 software specific car following parameters and the calibrated parameters for obtaining specified objectives are shown. It is observed that car following maximum headway was changed from 6 s to 4.5 s and mean of threshold was changed from 3.17 to 2 to obtain the goals of the study.

Table 4: Software specified car following parameters and calibrated value of parameters

Parameter	**Software Specified Value**	**Calibrated Value**
Free Flow Minimum Headway (sec)	0.50	0.50
Car-Following Maximum Headway (sec)	6.00	4.50
Mean of Threshold (s)	3.17	2.00
Standard Deviation	0.87	0.87
Stopped Headway (ft)	32.81	32.81

Table 5: Software specified lane changing parameters and calibrated value of parameters

Parameter	**Software Specified Value**	**Calibrated Value**
HV Threshold (m)	9.00	9.00
LV Average Time (sec)	1.80	0.80
LV Minimum Time (sec)	0.70	0.45
LV Maximum Time (sec)	3.00	2.00
LV Standard Deviation	1.50	1.50
LV Minimum Distance (m)	5.00	3.50
HV Average Time (sec)	2.50	2.50
HV Minimum Time (sec)	1.50	1.50
HV Maximum Time (sec)	5.00	5.00
HV Standard Deviation	1.00	1.00
HV Minimum Distance (m)	7.00	7.00

Table 5 illustrates that light vehicle average time, light vehicle minimum time and light vehicle maximum time values were changed from the software specified values for calibrating the lane changing parameters in the software.

The reason for changing those values was to see how the speed, flow and occupancy relationships change with the alteration in such values. And thus field condition was portrayed exactly on the simulation software and necessary conclusions were drawn observing the results.

3.5 Results

In order to draw conclusion that the simulation is a match to the field condition, the speed, flow and density relationship should be as shown in figure 3. These relationships were obtained by statistical analysis of the field data obtained from detectors.

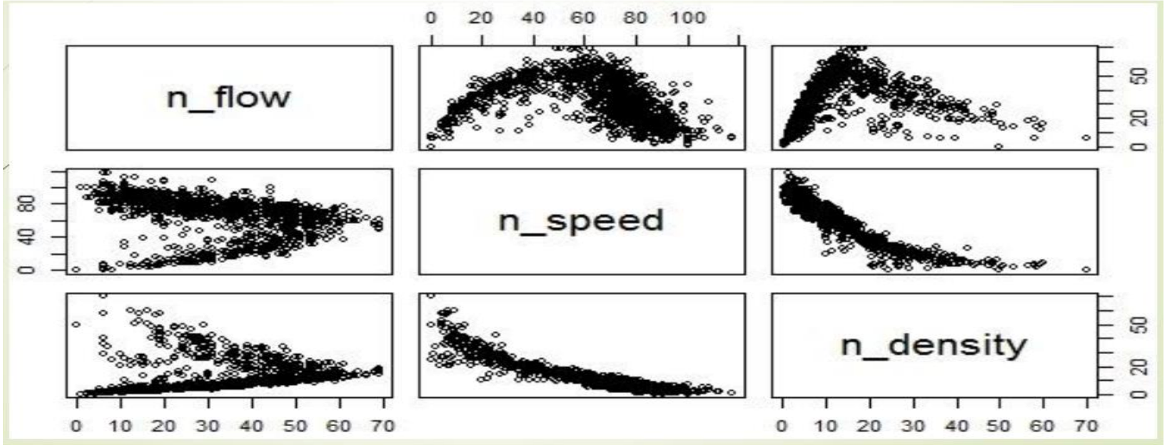

Figure 3: Relationship between flow, speed and density

The left hand side of figure 4 was obtained after the first simulation run in which no change in the software specified parameters were done. It is observed that most of the vehicles are operating at a very high speed rather than giving a good speed-flow relationship. Whereas, on the right hand side of figure 4 it is observed that the relationship has changed from the previous run. This change in relationship was observed due to calibration of the parameters as mentioned in the earlier section. It is understood by comparing the relationships that the relationship obtained after calibrating the parameters are much more satisfactory than that of the earlier.

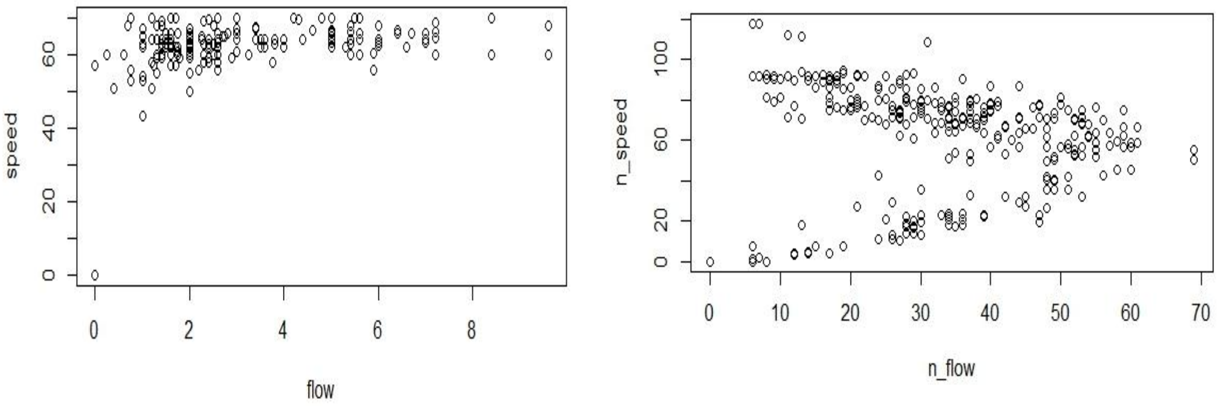

Figure 4: Flow vs Speed relationship with software specific value (left hand side) and Flow vs Speed relationship with calibrated value (right hand side)

4. CONCLUSIONS

Finding out realistic solution to ensure road safety is very important in transportation sector. In this regard it is necessary to define normal and hazardous traffic condition with a micro-simulation approach as micro-simulation approach is less time consuming and dangerous in defining hazardous traffic condition. In CUBE Dynasim car following and lane changing behaviour parameters were altered to create different flow patterns. Changing the values of car-following maximum threshold and mean of threshold value for car following rules and in case of lane changing behaviour changing of heavy vehicle threshold, light vehicle average time, light vehicle minimum time, light vehicle maximum time, light vehicle standard deviation, light vehicle minimum distance, heavy vehicle average time, heavy vehicle minimum time, heavy vehicle maximum time, heavy vehicle standard deviation, heavy vehicle minimum distance brought the best possible outcome. The limitation of the study could be the use of only 300 as input in CUBE Dynasim. This was done so owing to limitation of time.The constriction of time during analysis was there because of the fact that a huge amount of time was spent for learning the software and simulation model building. In future this study could be further used to find out the inclusion of interventions and their effects to turn a hazardous traffic condition back to normal. This study was done based on data of Japan if adequate data could be formulated such study could be carried out for expressways in Bangladesh as well.

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