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Short Communication
Using Monte Carlo Simulation for Vehicle Emission Estimation-A Case Study in Hong Kong

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Abstract

Background and Objectives: Air pollution caused by vehicular emission has been a public concern and is more seriously in Hong Kong which is a highly urbanized and congested city. Therefore, a study was conducted to observe the vehicular pollutant emission and concentration. This study intends to update the driving behavior in terms of vehicle speed and vehicle acceleration for heavy diesel vehicles in Hong Kong residential area. **Materials and Methods:** A total of over 900 min of data were collected by the car chasing technique for 93 heavy diesel vehicles in Shatin, one of the most crowd residential area in Hong Kong during the period November and December, 2019. A three dimensions speed-acceleration matrix and plot were developed by the sampled result. Project team further applied the Hong Kong based speed-acceleration probability distribution to the tunnel mass balance emission model for CO and NO vehicle emission estimation. **Results:** A Hong Kong based three-dimension speed-acceleration-frequency matrix was successfully developed. Monte Carlo simulation were further carried out for 1000 times within obtained driving cycle and then further calculating the CO and NO emission factor. It was observed that in average one heavy diesel vehicles has emitted 6.5 g CO and 7.1 g NO for one trip in residential area (around 10 km). **Conclusion:** This research project focuses on the interaction effect between vehicle speed and acceleration and showed there was interaction effect. This method is simple and extremely good under limited budgets. Statistical Monte Carlo simulation further improved the accuracy of the driving cycle modeling.

Key words: Driving behavior, driving cycle, speed-acceleration pattern, tunnel mass balance, emission model

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Vehicle emission estimation is a very traditional topic in pollution control. An accuracy estimation value in vehicle emission could help government for further town planning. Travel based model and fuel consumption based model are two main ways to estimate vehicle emission[1]. For fuel consumption based model, driving behavior is an important factor. Number of statistical and computer models were developed in past decent years for vehicle emission estimation. Average speed emission model was firstly developed for fuel consumption models[2]. The uses of driving pattern which affecting fuel consumption and led to exhaust emission were further applied for emission estimation. Driving cycle and instantaneous driving cycle were both focus on speed verses time[3]. However, the interaction effect between vehicle speed and acceleration were not covered in most of the models due to the difficulty of including interaction effect in statistical modelling[4].

In 2000, the first on-road speed-time driving behaviors sampling was by an instrumented diesel vehicle along two fixed routes located in two urban districts in Hong Kong. The collected data were analyzed and compared with mandatory driving cycles used elsewhere. It was found that none of these mandatory cycles could satisfactorily describe the driving characteristics in Hong Kong. A unique driving cycle was therefore developed for Hong Kong. In 2007, a practical methodology was developed for constructing a representative driving cycle reflecting the real-world driving conditions is developed for vehicle emissions testing and estimation[5]. They claimed that the method is easy to follow and the driving cycles are comparative to other renounced cycles. However, according to the researchers, their method is suffering from a number of limitations such as picking the representative routes by annual average daily traffic data, but not the specific data for each type of vehicles. Furthermore, in their driving cycle development, they focused in urban area, most of the vehicles failed to perform high speed acceleration in their research. Furthermore, the research also concluded and suggested that further researches should record more speed data in sub-urban areas. Furthermore, pervious research in driving cycle did not study the relationship between vehicle speed and vehicle acceleration. It leads to lack of information on apply an updated statistical Monte Carlo vehicle emission estimation. Furthermore, the driving cycle for diesel vehicles in residential area in Hong Kong did not update since 2007.

Vehicular pollution levels depend on many factors, including traffic volume, vehicle mix, road type and meteorology. In measuring vehicle gaseous emissions under extremely congested traffic conditions in traffic hot-spots in Macao, researchers used a mobile laboratory which was an instrument vehicle equipped with analyzers and sensors and a variety of vehicles were followed for vehicle-following experiments[6]. Driving characteristics of Hong Kong buses were conducted in 2019 and found that there were significantly different from other worldwide bus driving cycles[7]. This reflected the unique driving patterns of buses in Hong Kong characterized by the long idling proportion due to the long dwell times at bus stops and very frequent stop-and-start operations due to individual bus stop and closely spaced signal junctions. Understanding of Hong Kong driving cycle, especially the understanding of relatively high acceleration and deceleration pattern of those vehicles were investigated in this study.

MATERIALS AND METHODS

Study area: The data sampling of vehicle speed was conducted from October-November, 2019. They were recorded in three timeslots; (1) In the morning (06:00-11:00), (2) Non-peak hours (12:00-15:00) and (3) In the evening (17:00-21:00) in Shatin. Shatin is a city along Shing Mun river in Sha Tin district of East New Territories, Hong Kong. It is one of Hong Kong's most crowd residential areas. According to the 2011, population census was 630,273 within an area of 35.87 km^2. The speed limit for the residential area in Hong Kong is 50 km h^{-1}.

Driving cycle development: Traditional driving cycle is the micro-trips-based approach in which a large sample of time series of speeds (trips) are divided into micro-segments (known as micro-trips) which are speed vs. time sections with initial and final speeds equal to zero[8,9]. Another newly adopted approach is Monte Carlo technique by apply and developing a $M \times N$ matrix for the speed acceleration frequency distribution[10].

Speed and acceleration data collection and measurement methods: It is obvious that vehicle speed and acceleration are one of the main factors reflecting one's driving behavior. In order to explore the interaction effect between vehicle speed and acceleration, on road sampling was carried out. Instrumented vehicles provide a way to gather information about vehicle operation and traffic conditions in the real world environment. To capture the real world vehicle speed and other relevant parameters, the car chasing method is the most direct method[11-13]. It is a very common technique used in

developing driving cycles. This method used to collect speed and acceleration data for the chasing heavy vehicles. The three-dimension speed-acceleration profile was recorded by chasing vehicles.

Velocity was recorded every second. Thirteen streets and roads were observed. Six streets in a middle-sized town of 50000 inhabitants were chosen to represent different traffic flows. Two motor ways, two express roads and three highways in the main road network were chosen to represent steady and unsteady traffic flows.

After reviewing several sampling methods, car chasing techniques was used in this study. The GPS used for the speed and acceleration measurement. Vehicle velocity was recorded in every 0.1 sec and the acceleration was calculated by the 2 sec interval measurement. A Toyota Noah (1998 c.c.) equipped with GPS was used to collect a set of continuous speed and acceleration data. After collecting the data, the three dimensions vehicle speed-acceleration matrix was developed.

RESULTS AND DISCUSSION

In this study, car chasing method was used to develop the Hong Kong based driving cycle for heavy duty vehicles in residual area. A statistical speed-acceleration matrix was developed by the driving cycle. Monte Carlo simulation was further applied on vehicle emission estimation.

Car chasing sampling result: In this survey, the most crucial driving behaviors vehicle speed and acceleration were focused. A total of 908 min of data were collected with the car chasing technique for 93 heavy diesel vehicles. The average vehicle speed of sampling is 19.44 km h^{-1} with standard deviation of 4.2 km h^{-1}. Due to the sampling was conducted in residential area, the average acceleration is approximate to zero and no extreme acceleration or deceleration were obtained. The summary of sampled data showed in the Table 1.

Classical statistics was used for testing if the data exhibit a normal frequency distribution. Anderson-Darling goodness-of-fit tests performed to confirmed that the distribution of vehicle speed was normally distributed with p-values greater than 0.37. This result indicated that with a probability of 95%, those distributions fit a normal distribution with mean and standard deviation equals to 19.44 and 4.2 km h^{-1}, respectively.

Three-dimension speed-acceleration frequency plot: The 3D plot is showed in Fig. 1. The 3D plot revealed that mostly frequency was conducted at 30 km h^{-1} with approximately to zero acceleration. This was also a very common case in crown residential are in Hong Kong. Furthermore, there was one more peak in terms of frequency when vehicle speed is below 5 km h^{-1} and also about zero acceleration. By the record in the record sheet, project team found that it mainly due to traffic jam and traffic lights.

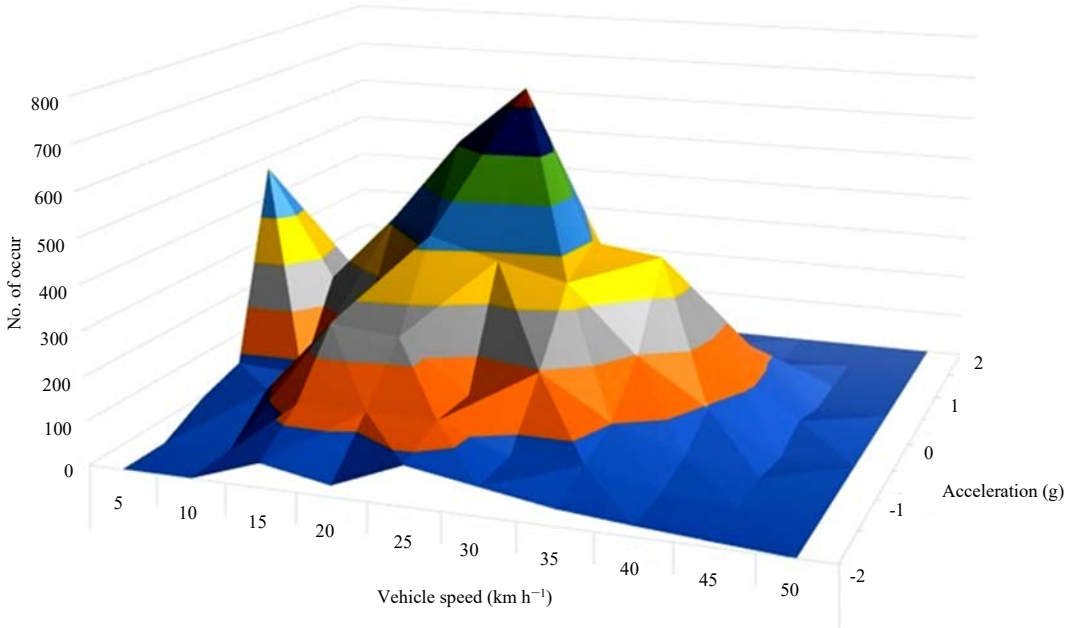

Fig. 1: 3D plot of showing the relationship between vehicle speed and acceleration

Table 1: Summary of sampled data

Parameters	Average	SD	Maximum	Minimum
Speed (km h^{-1})	19.44	4.2	43.8	0.0
Acceleration (g)	-0.07	0.3	2.2	-2.4

Table 2: Hong Kong Cross Harbour tunnel, the CO and NO emission factor for diesel vehicle speed[14]

Speed (km h^{-1})	CO emission factor (g/vehicle km)	NO emission factor (g/vehicle km)
10	1.40	1.36
30	0.43	0.44
60	0.25	0.28

Vehicle emission estimation: Driving cycle was usually applied on vehicle emission estimation. According to the finding in Hong Kong Cross Harbour tunnel, the CO and NO emission factor for diesel vehicle speed were shown[14] in Table 2. In that study, 9057 diesel vehicles emission data were measured in Hong Kong.

Table 2 revealed the result that both CO and NO emission at relatively high level when vehicle is driving at low speed. The pollutant emission decrease sharply when the speed increases. The inverse proportion relationship was confirmed in both CO and NO.

Monte Carlo simulation was applied in vehicle emission estimation by using the new developed speed-acceleration-frequency profile as posterior distribution. Carlo simulations were carried out for 1000 times within our obtained driving cycle to simulate the driving pattern for heavy duty vehicle to drive within Hong Kong residential area for 10 km. The tunnel based mass emission factor by Chan and Ning[14] were for applied on finding the vehicle emission for CO and NO. It was observed that in average one heavy diesel vehicles has emitted 1.4 g CO and 1.36 g NO for one trip in Hong Kong residential area (around 10 km).

Speed-acceleration probability distribution was used as another way to presenting the driving cycle in urban area[1,8,15,16]. Similar results on relatively low frequency occur in high acceleration (>2 g) were obtained. Furthermore, previous studies[15,16] reported that urban driving cycle face the problem of long idling time due to traffic jam and traffic light. Similar to findings of this study, both draw the same conclusion on average speed is not the best variable to present the overall driving behavior. Researchers developed driving cycle in urban area of Mexico[10] and confirmed that the idling time for vehicle should be consider as an external factor. Similar to this study, the Mexico speed-acceleration distribution showed normally distributed by Anderson-Darling goodness-of fit test. Pervious Hong Kong based driving cycle obtained data by instantaneous data and use average speed and acceleration to present the driving behavior[4,5]. This research firstly filled the knowledge gap of lack of speed-acceleration-frequency data for Hong Kong based residential area. Furthermore, the application of Monte Carlo simulation successfully estimated vehicle emission by non-average speed driving behavior. The result of Monte Carlo was closer to practical. For same traffic data that apply on Chan and Ning[14] model for constant average speed assumption, the CO and NO for 10 km should be 9.3 and 9 g, respectively. That representing 43 and 26% more than Monte Carlo simulation.

Driving cycle is an old topic in environmental science, but researchers are still working on the best way to obtain the mostly suitable driving cycle. However, it should be noted that each method has its own advantage and disadvantages. This study focused on the interaction effect between vehicle speed and acceleration and showed the interaction effect by 3D plot and Anderson-Darling goodness-of-fit tests. This method is simple and extremely good for limited budgets. Also, for the chase car method, route selection is not vital since the car follows the actual road user. This method may suffer to the sample error, but it could be easily overcome by increasing the sample size. The profile could further apply in vehicle emission estimation and monitoring. In terms of the normal frequency distribution on driving behavior in urban driving condition, further statistical measurement should carry out. The conformation of normal frequency distribution behavior could improve the application of simulation and the possibility of apply Bayesian estimation.

CONCLUSION

Traditional mass balance model assumed constant speed for emission estimation, but that is nearly impossible to have constant speed in real world road situation. This study developed the speed-probability profile for 2019 Hong Kong heavy diesel vehicles in Shatin. Applied Monte Carlo simulation estimate the vehicle emission of CO and NO in grams. This method is easy to handle and closer to the realistic vehicle emission estimation.

SIGNIFICANCE STATEMENT

This study discovered the importance of taking into account of speed-acceleration interaction effect in vehicle emission that can be beneficial for future statistical vehicle emission model. With the use of statistical Monte Carlo simulation, vehicle emission could be easily estimate by the interaction effect in driving behaviors. This study will help the researchers to uncover the critical areas of improving driving behavior simulation that many researchers were not able to explore.

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