An Integrated Emission and Dispersion Model under Mixed Traffic Conditions

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Abstract: This paper develops the emission and dispersion model based on our previously proposed and validated mixed traffic cell-transmission model (MCTM). Additionally, the emission coefficients of various types of motor vehicles and the Gaussian puff dispersion model are integrated into the MCTM model to simulate the dynamic emission concentration along the roadway. To investigate the applicability of the proposed model, a signalized intersection under various traffic conditions and signal timing plans are simulated and compared. Taking one of pollutants, carbon monoxide (CO), as example, dynamic CO concentrations of a total of 10 spots at different distances from the intersections are analyzed and compared. Results show that the CO concentration decreases as the distance from the intersection increases. Moreover, it is interesting to note that the total CO emissions will increase as the intersection delay increases, but the CO concentration does not remarkably increase.

Keywords: Mixed Traffic, Cell Transmission Model, Emissions, Dispersion.

1. INTRODUCTION

The ever-increasing usage of fossil-fuel vehicles has long caused a major source of air pollutants and greenhouse gas emissions on the planet. Traffic emission and its dispersion are influenced by vehicle moving conditions. In urbanized areas especially near the major intersections where recurrent heavy traffics often queue up with start-and-stop conditions, the frequent occurrence of high emission concentration can harm human's physical health. Not only directly affected by the amount of discharged emissions from vehicles, emission concentration can also be affected by other environmental situations including building, wind and temperature. To effectively reduce adverse impacts of highly-concentrated traffic emissions, it is imperative to introduce new traffic control concepts that would minimize the local emission concentration rather than conventional measures of effectiveness (MOEs) like queue lengths and total delays. As such, developing a signal control model that is capable of replicating traffic behaviors and evaluating emission concentration is an important issue calling for in-depth exploration.

In the past, most signal control designs aimed to minimize traffic delays; recently, however, more academic studies and pragmatic applications have taken fuel consumption and traffic emissions into account. For example, Li *et al.* (2004) optimized the cycle length of signalized intersections by minimizing the weighted sum of traffic quality (delays), fuel consumption and emissions. Huang *et al.* (2010) proposed a bi-level programming model to minimize the total exhaust emissions (including intersection and road-section emissions) on urban network through road capacity enhancement and signal cycle adjustment. Li *et al.*

(2011) proposed a two-stage approach to investigate the environmental impacts of signal timing on vehicle emissions by trading-off vehicle delays and number of stops in the first stage and then estimating vehicle emissions in the second stage. Fuel consumption and traffic emissions are closely related and both are affected by vehicle maneuvers including acceleration, deceleration, cruising, and idling. Fuel consumption rate and emission rate can be a function of vehicle speeds. However, estimation of emission concentration is a completely different story, much more complicated than estimation of traffic emissions. It depends heavily on the ways how traffic emissions disperse, which is related to the amount of vehicle emissions as well as such factors as surrounding buildings, wind directions, and temperature conditions. Dispersed emissions will create a certain level of concentration at any specific spatiotemporal point. In environment-sensitive areas such as schools and hospitals, it requires to regulate the emission concentration once it reaches a certain level. And this should be taken into account in optimizing the traffic signal control model.

There have been numerous studies considering the estimation and analysis of emissions and dispersion. Several researches employed the Gaussian line source formulation (e.g. GFLSM, CALINE4, IITLS) for predicting the air quality impacts of emissions from road traffic (Ganguly and Broderick, 2008; Ganguly and Broderick, 2010). Many researchers simultaneously employed the traffic simulation model (e.g. VISSIM, CTM, VISUM, PARAMICS), the traffic emission model for line sources (e.g. TREM, TEDS, CALINE, MOBILE) and the local scale dispersion model (e.g. VADIS, Gaussian dispersion model) to simulate the dispersion phenomenon. For example, Borrego *et al.* (2003) used TREM to estimate traffic emissions and VADIS to simulate the emission dispersion to assess the air quality in Lisbon. Lin and Ge (2006) proposed an integrated model to assess roadside air quality by combining a macroscopic traffic simulation model (CTM), traffic emission model (CALINE) and emission dispersion model (Gaussian). Ishaque and Noland (2008) analyzed the CO emissions by using microscopic traffic simulation model (VISSIM) and found that longer cycle length tended to reduce total vehicle emissions but shorter cycle length would reduce the possibility of pedestrians waiting and exposing to emissions. What seems lacking, however, is incorporation of traffic emissions and dispersion into an adaptive signal control model with consideration of various pollutants emission concentration, including CO, HC, NOx, and PM. Besides, previous traffic simulation models dealing with cars' emission rates do not consider motorcycles. As motorcycles are ubiquitous in many Asian urban streets, the traffic simulation model should replicate the mixed traffic behaviors; more importantly, the emissions model should also distinguish cars' emission rates from motorcycles'. The numbers of car and motorcycle can be estimated by MCTM model. The emission of car and motorcycle can be calculated by different parameters, respectively.

Although it is well-known that microscopic traffic flow models usually better simulate traffic behaviors than macroscopic ones (e.g. CTM), to attempt to keep the integrated model remain computation efficiency so as to be applied to optimize signal timing or to simulate emission concentration of a much larger network, this study adopts macroscopic cell-based traffic flow models to simulate traffic behaviors.

Based on this, this study aims to integrate three sub-models: mixed traffic cell-transmission model (MCTM), traffic emission model, and Gaussian puff dispersion model. It aims to find the relationship between total emissions, emission concentration and delays along a road stretch. This study also analysis the effect of emission concentration at intersection upstream and downstream. This study employs the MCTM (Chiou and Hsieh, 2012) as the mixed traffic maneuvers, the TEDS 7.0 line source emissions database as the basis of emission estimation, and the Gaussian puff dispersion model as a tool to simulate the emission dispersion as well as to predict the spatiotemporal emission concentration.

The rest part is organized as follows. Section 2 briefs the rationales for developing mixed traffic flow model, traffic emission model, and emission dispersion model. Section 3 presents the model results and comparisons with a pre-timed control strategy. Finally, the concluding remarks and suggestions for future research follow.

2. THE RATIONALES

2.1 Mixed traffic cell-transmission model

Since the microscopic models need high computational burden, it is difficult to simulate the traffic behaviors in real time. The cell-based traffic simulator uses several simple equations to govern traffic movements, and need lower computational burden. cell-based traffic simulator can simulate traffic behavior in real time. For this reason, a cell-based traffic simulator, like the CTM models coined by Daganzo (1994, 1995), is used in this study because it is more efficient than any microscopic traffic simulator. The CTM model uses several simple equations to govern traffic movements along the roadway, which is represented by a series of equal-length cells. The CTM assumes the vehicles are homogenous in each cells. These equations are expressed as follows:

$$n_i(t+1) = n_i(t) + y_i(t) - y_{i+1}(t) \tag{1}$$

$$y_i(t) = \min\{n_{i-1}(t), q_{mi}(t), \beta[N_i(t) - n_i(t)]\}; \quad \beta = \begin{cases} 1, \text{ if } n_{i-1}(t) \le q_{mi}(t) \\ \dfrac{w}{v}, \text{ if } n_{i-1}(t) \ge q_{mi}(t) \end{cases} \tag{2}$$

Based on the conventional CTM, Chiou and Hsieh (2012) have recently developed and validated a MCTM to elucidate mixed traffic flows composed of cars and motorcycles. The above variable $n_i(t)$ in Eq. (2) has been decomposed into $n_i^c(t)$ and $n_i^m(t)$ to represent the numbers of cars and motorcycles in cell *i* at time *t*, respectively. Thus, Eq. (1) can be revised as:

$$\begin{aligned} n_i^c(t+1) &= n_i^c(t) + y_i^c(t) - y_{i+1}^c(t) \\ n_i^m(t+1) &= n_i^m(t) + y_i^m(t) - y_{i+1}^m(t) \end{aligned} \tag{3}$$

Both types of vehicles exhibit rather different behaviors in competing the roadway capacity and the remaining storage space. Thus, the parameters of MCTM, including maximum flow rate, maximum storage capacity, and remaining storage capacity, are dynamically adjusted and allocated according to the mixture ratio. Three situations are further considered as follows:

1) Free flow: In this situation, the flow and density of cars and motorcycles, in upstream cell, are less than maximum flow and remaining capacity of downstream cell. This condition refers to the first part of Eq. (3) in which the vehicles can transmit from upstream to downstream without deferring.

2) Competing at the maximum flow ($q_{mi}(t)$): This situation occurs when the number of vehicles in upstream cell exceeds maximum flow. Thus, cars and motorcycles compete with one another to transmit from upstream cells to downstream. Based on the field observations, the interferences between cars and motorcycles will be drastically increased as the mixture ratio becomes larger. Thus, an entropy concept dynamically adjusting PCE (α) to depict the

competition relationship can be defined as follows:

$$R_m^Q(n_{i-1}^c(t), n_{i-1}^m(t)) = \frac{\eta \times n_{i-1}^m(t)}{\eta \times n_{i-1}^m(t) + n_{i-1}^c(t)} \tag{4}$$

where,

η denotes PCE of motorcycles, which is assumed linearly increasing with the entropy from a base value PCE (α).

3) Competing with the remaining storage capacity ($N_i(t) - n_i(t)$): This situation occurs when the remaining storage capacity in the downstream cells cannot accommodate all vehicles transmitted from the upstream. Let $R_m^S(n_{i-1}^c(t), n_{i-1}^m(t))$ denote the space competition function which allocates the remaining storage space between cars and motorcycles moving from upstream to downstream. The remaining storage capacity is allocated to cars ($S_i^c(t)$) and motorcycles ($S_i^m(t)$) as follows:

$$S_i^c(t) = R_m^S(n_{i-1}^c(t), n_{i-1}^m(t)) \times S_i(t) \tag{5}$$

$$S_i^m(t) = \frac{[1 - R_m^S(n_{i-1}^c(t), n_{i-1}^m(t))] \times S_i(t)}{l} \tag{6}$$

where,

l : the space occupancy ratio of a car over a motorcycle.

According to Logghe and Immers (2008), vehicles with higher density on road have the advantages of moving forward. Thus, the space competition function can be expressed as:

$$R_m^S(n_{i-1}^c(t), n_{i-1}^m(t)) = \frac{n_{i-1}^m(t)}{n_{i-1}^m + l \times n_{i-1}^c(t)} \tag{7}$$

In sum, to depict the MCTM with cars and motorcycles, Eqs. (1) and (2) can be expressed as Eqs. (8) and (9):

$$\begin{aligned} n_i^c(t+1) &= n_i^c(t) + y_i^c(t) - y_{i+1}^c(t) \\ n_i^m(t+1) &= n_i^m(t) + y_i^m(t) - y_{i+1}^m(t) \end{aligned} \tag{8}$$

$$\begin{aligned} y_i^c(t) &= \min\{n_{i-1}^c(t), [1 - R_m^Q(n_{i-1}^c(t), n_{i-1}^m(t))] \times q_{mi}(t), \frac{[1 - R_m^S(n_{i-1}^c(t), n_{i-1}^m(t))] \times S_i(t)}{l}\} \\ y_i^m(t) &= \min\{n_{i-1}^m(t), \frac{[R_m^Q(n_{i-1}^c(t), n_{i-1}^m(t)) \times q_{mi}(t)]}{\alpha}, R_m^S(n_{i-1}^c(t), n_{i-1}^m(t)) \times S_i(t)\} \end{aligned} \tag{9}$$

2.2. Traffic Emission Model

To estimate the road traffic emission, the TEDS 7.0 line source emissions database is employed in this study. In Taiwan, the data of TEDS 7.0 compose of five classes of vehicles, including car, pickup truck, bus, two-stroke motorcycle and four-stroke motorcycle. The traffic emission pollutants mainly include SO_X, NO_X, THC, CO, Pb and PM2.5, of which CO takes 55.9% of total emission. Thus, CO is used to represent the major traffic emission. Among these five classes of vehicles, car and four-stroke motorcycle have the highest percentages of CO emissions. Hence, this study employs the emission coefficients of car and four-stroke motorcycle to estimate the traffic emissions, which are calculated by the following two equations, respectively.

$$0.036\text{-}0.00035V+0.000078V^2\text{-}0.0000016142V^3+1.005\times10^{-8}V^4 \quad (10)$$
$$0.025\text{-}0.00075V+0.000063V^2\text{-}0.000001182V^3+7.0755\times10^{-9}V^4 \quad (11)$$

where,

V : the vehicle speed.

It should be noted that the emissions of idling stop are not estimated in TED 7.0 database; this study directly employs the research results by Lin *et al.* (2000) and Chang (1996) to estimate the emissions of idling stop for car and four-stroke motorcycles. The relationship of traffic emission and speed is showed in Figure 1.

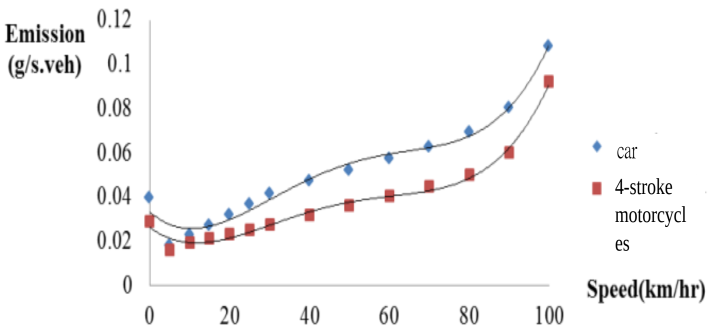

Figure 1. Relationship of traffic emission and speed

2.3 Emission Concentration Model

Emission dispersion can be estimated by the Gaussian puff model. Nagendra and Khare (2002) employed the Gaussian puff model to develop the line source emission model (LSEM), which is based on the concentration detected by the receptors. Summing up the concentrations from all emission sources makes up a line source, and the emission concentration can then be formulated as:

$$\bar{c}(x,y,z,t)=\frac{Q}{(2\pi)^{3/2}}\int_0^t\frac{1}{\sigma_x\sigma_y\sigma_z}\exp\{-\frac{(x-\bar{u}t')^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}-\frac{z'^2}{2\sigma_z^2}\}dt' \quad (12)$$

where,

Q :the line source strength (unit/s),

$\sigma_x, \sigma_y, \sigma_z$: the standard deviation of concentration in *x*, *y* and *z* directions,

x, *y*, *z* : the horizontal and vertical dispersion directions and the receptor's height above the ground level, respectively,

z' : the difference of the receptor's height and the line source's height,

$\bar{u}$: the mean wind speed at the line source's height, and

t : the time period of dispersion.

3. AN EXPERIMENTAL EXAMPLE

To demonstrate the proposed model, an experimental four-leg intersection (Figure 1) is presented. Since the emission concentration will be caused by many reasons, including traffic factors (e.g. through moving traffic, turning traffic, queuing traffic at each of directions), road factors (e.g. surface condition, road slope…) and meteorological factors (e.g. temperature, wind direction and magnitude …). To simplify the analysis, we assume the road factors and meteorological factors remain the unchanged during the simulation. Additionally, we assume no turning traffics and traffic flow at four directions are the same.

3.1 Parameter Settings

The parameters of the MCTM model are set as: free-flow speed=40 km/h, time step=2 seconds, k_j=90 veh/km/lane. Assume that the intersection has two lanes ($N_i(t)$=3.6 cars/cell for all i and t) in each approach with saturation flow of 1800 pcu/hr/lane ($q_{mi}(t)$=2.00veh/time step for all i and t). The parameters of the emission dispersion model are set as: wind speed= 1.5 m/s, surface friction speed=0.136 m/s. To estimate the emission concentration, the concentration detection receptor is placed every 22 meters along the roadside (Figure 2). The real 15 minutes traffic flow data of Taipei city are given in Figure 3. In order to estimate the emission concentration of four directions, this study assumes that each direction has the same traffic flow rate. The signal control strategies of the variable cycle length (VCL) and constant cycle length (CCL) are used to evaluate the effect of signal control and compare the intersection delay with emission concentration. The signal control strategies are assumed as two phases. The cycle length and time split of each signal control strategies are shown in Table 1. In order to reflect the condition, the 180s cycle length is used in this study, which is common in busy intersections in Taiwan.

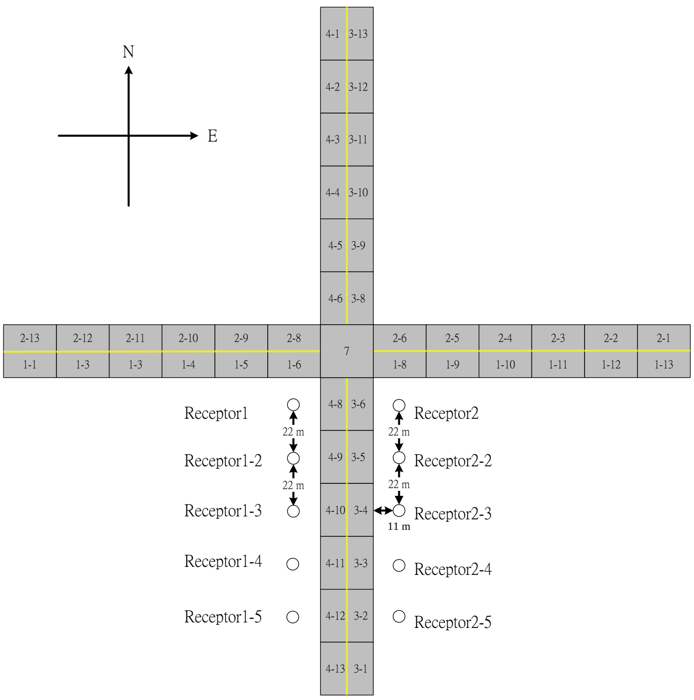

Figure 2. Configuration of the experimental intersection

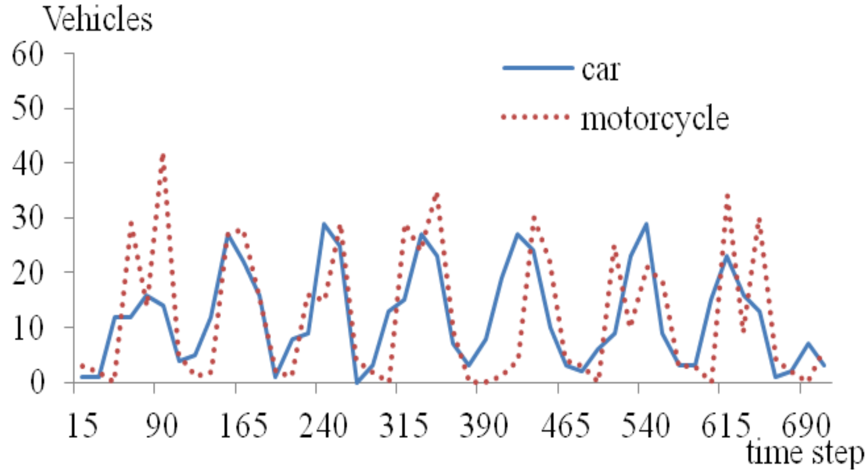

Figure 3. Flow rates at the experimental intersection

Table 1. Signal control strategies and timing plans

Signal control strategies	Signal timing plans	Cycle length (seconds)	Green time at east westbound (seconds)	Green time at north southbound (seconds)
Variable cycle length	S1-1	80	48	32
	S1-2	120	72	48
	S1-3	160	96	64
Constant cycle length	S2-1	180	70	110
	S2-2		90	90
	S2-3		120	60

3.2 Model Results

A total of six signal timing plans under two signal control strategies are used to investigate the relationship between traffic flow and emission concentration. Table 2 shows the estimated carbon monoxide (CO) emissions at the intersection under various signal timing plans. Note that the emissions get higher as the cycle length becomes longer. Taking timing plans S1-2 and S1-3 of the VCL strategy as examples, the total emissions of S1-2 (cycle=120 seconds), 4559.72g, are lower than those of S1-3 (cycle=160 seconds), 4758.24g. As to the CCL strategy, the emissions decrease as the green time of eastbound increases.

Table 2. Estimated emissions of different directions (gram)

Direction	Signal control strategy					
	Variable cycle length			Constant cycle length		
	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3
East westbound	1810.57	1973.74	2246.23	2240.70	1801.78	1492.38
North southbound	2723.30	2585.98	2512.01	2510.37	3073.71	3688.50
Total	4533.88	4559.72	4758.24	4751.08	4875.50	5180.89

Table 3 shows the emission concentration of two receptors. As to the Receptor 1, emission concentration at eastbound is the major source, followed by the southbound, suggesting the most serious impact to emission concentration comes from the nearest traffic flow. In contrast, the Receptor 2 receives the largest emissions from southbound traffic, followed by westbound traffic. However, in terms of total emission concentration, similar emission concentration is measured at both receptors. Similarly, for VCL strategy, the emission concentration becomes higher as the cycle length increases. As to the CCL strategy, the emission concentration reduces as the green time for west-eastbound traffic increases. However, it should be noted that the emission concentration is also affected by other environment factors, e.g. wind speed, wind direction and temperature. Based on these result, there are different emission concentration for optimum cycle length and signal timing at each receptor. To assume the receptor 1 and receptor 2 are the specific sensitive areas, the S2-3 strategy is better than other strategies.

Table3. Estimated emission concentration at receptors (ppm)

Signal timing plans	Receptor 1					Receptor 2				
	East	West	South	North	Total	East	West	South	North	Total
S1-1	0.22	0.08	0.15	0.12	**0.56**	0.11	0.14	0.25	0.08	**0.58**
S1-2	0.24	0.08	0.14	0.11	**0.57**	0.11	0.17	0.23	0.07	**0.58**
S1-3	0.26	0.08	0.13	0.11	**0.58**	0.12	0.19	0.21	0.07	**0.59**
S2-1	0.27	0.08	0.12	0.10	**0.57**	0.11	0.18	0.20	0.07	**0.55**
S2-2	0.21	0.08	0.13	0.11	**0.53**	0.11	0.14	0.22	0.07	**0.54**
S2-3	0.14	0.07	0.15	0.11	**0.47**	0.10	0.09	0.25	0.08	**0.51**

3.3 Comparison

To investigate the effect of intersection delay to total emissions and emission concentration, this paper compares the total vehicle delays with total emissions and emission concentration under various signal timing plans as shown in Table 4. The results show that total emissions increases as TVD becomes higher. For example, the total vehicle delays of S1-1, S1-2 and S1-3 plans are 27.15, 32.64 and 38.88 vehicle-hours, respectively, and their total emissions are 4533.88 g, 4559.72 g and 4758.24 g, respectively. Both total vehicle delays and total emissions are in the same order. Similarly, total emissions of signal timing plans of S2-1, S2-2, and S2-3 are also in the same order of total vehicle delays of three plans. In other words, traditional signal control model in minimizing total vehicle delays will simultaneously minimize total emissions.

However, the emission concentration of various signal timing plans does not follow the same order of the corresponding total emissions and total vehicle delays. It is because that emission concentration would be strengthened if emissions are continuously added onto a specific spot. In contrast, the concentration would become lighter and evaporated if emissions are interrupted. Especially, for the signal timing plans with longer cycle length, the start-and-stop conditions are less frequently happened. Although the total vehicle delays are high, the concentration level is low because the emissions are not able to be continuously accumulated. That is, in our experimental intersection with given traffic flows and timing plans, shorter cycle length is favored, if the goal of signal control is to minimize the total vehicle delays or total emissions, contrasting to the goal of minimizing emission concentration. However, the later is the key factor for the health consideration.

Table 4. Comparison of total vehicle delays (TVD) under various signal timing plans

Signal timing plans	TVD (vehicle-hours)		
	East westbound	North southbound	Total
S1-1	5.76	21.39	27.15
S1-2	6.95	25.69	32.64
S1-3	15.84	23.04	38.88
S2-1	12.14	24.74	36.88
S2-2	4.44	38.29	42.73
S2-3	0.99	59.19	60.18

This paper also compares the emission concentration at different locations. Figure 4 shows the evolution of emission concentration of five receptors at different locations. Receptor 1 is the receptor nearest to the intersection, so it has the highest concentration among receptors at most time. However, when the queuing vehicles are piled over Receptor 1-5 (distance of 99 m from intersection stop line), making the emission concentration of Receptor 1-5 rapidly grow and even is higher than that of Receptor 1 during the traffic discharging period.

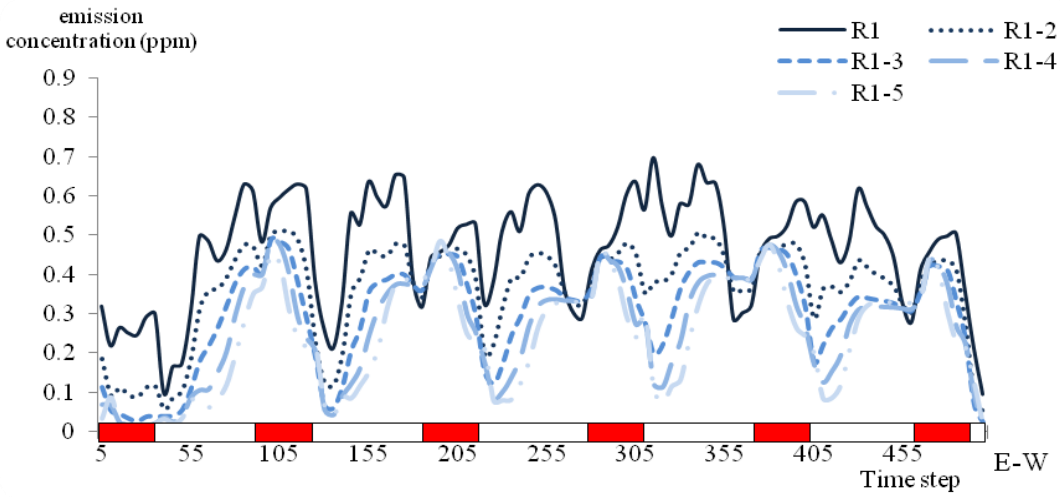

Figure 4. The relationship between receptor and concentration

4. CONCLUDING REMARKS

Exposures to the environment of high concentration level of air pollutions, such as CO, HC, NOx, emitted by motor vehicles are harmful to our health. However, most of signal control models aim to minimize the total travel time or total vehicle delays instead to keep the emission concentration at specific sensitive areas, such as hospitals and schools, below a certain level. To do so, an effective and efficient simulation model for simulating traffic behaviors, traffic emissions, and emission dispersion is required.

Based on this, this paper develops emission and dispersion model in mixed traffic contexts composed of cars and motorcycles, so as to evaluate and optimize the signal control strategies. The proposed model comprises three sub-models: mixed traffic flow model, traffic emission model, and emission dispersion model, wherein mixed traffic behaviors are replicated by the mixed traffic cell-transmission model, traffic emissions are estimated by TEDS 7.0 line source emissions database, and emission concentration is estimated by the

Gaussian puff model. The proposed model is verified at an experimental intersection and the emission is compared with different signal control strategies and signal timing plans. The results show that the longer cycle length could bring higher vehicle delays and emissions, but the lower emission concentration. In order to clearly investigate the effect of traffic flows and signal timing plans on emission concentration, the experimental example in this study assumes no turning traffic and same traffic flow of all directions; however, due to the flexibility of MCTM models, the proposed integrated model can easily further consider turning traffic and various traffic flow patterns.

Due to mixed traffic prevailed in many Asian urban streets, this study attempts to replicate the mixed traffic behaviors and then use of different emission rates for cars and motorcycles to estimate emissions. However, it should be noted that even for cars, the emission rate should vary according to different engine sizes, car age, and even car brand. Detailed parameter settings should be more elaborated to better estimate the traffic emissions. Additionally, the emission concentration estimated by the proposed model has not been validated by field measurement. Furthermore, the mixed traffic flow model can be extend to consider the turning traffics and the multi-phase signal control plans can be reflected by different traffic model. Last but not least, the proposed model can be applied to optimize signal timing plans and multi-phase signal control plans, which may better accommodate heavy turning traffic at some major intersections.

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