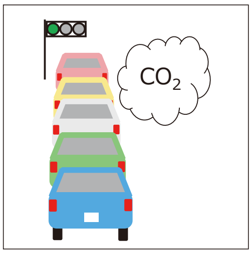

A CO_2 Emissions Calculation Model for Evaluation of Traffic Signal Control

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Climate change poses a global challenge that necessitates the reduction of carbon dioxide (CO_2) emissions. To reduce CO_2 emissions from motor vehicles, which are major emission sources, it is important not only to improve vehicle exhaust performance, but also to improve infrastructure such as traffic signal control at intersections to mitigate traffic congestion and energy consumption. A quantitative evaluation of the effects resulting from traffic signal control improvements is essential for their dissemination. Currently, however, there is no well-established method to calculate CO_2 emissions of vehicles traveling through intersections. We have developed a CO_2 emissions calculation model intended for widespread adoption. This model facilitates the quantitative evaluation of CO_2 emissions reduction resulting from traffic signal control improvements.

Keywords: traffic signal control, CO_2 emissions, effect verification

1. Introduction

Climate change is a challenge to the global community, and CO_2 emissions need to be reduced. Motor vehicles are major CO_2 emission sources and, in Japan, account for 15.5% of the country's total CO_2 emissions.(1) To reduce the volume of CO_2 emitted by motor vehicles, on the one hand, measures should be implemented on the part of vehicles, such as improved fuel efficiency and electrification (HEVs and EVs); on the other hand, it is also important to improve infrastructure for vehicles to travel with less energy consumption, for example, by improving traffic signal control at intersections for reduced traffic congestion.

The improvement of traffic signal control at intersections contributes to mitigated congestion and reduces the number of acceleration, deceleration, starts and stops of vehicles at the intersection. Consequently, CO_2 emissions will decrease. In this case, however, the reduced CO_2 emissions are not attributed to the manufacture or use of traffic signal control systems but rather to vehicles traveling through intersections. Accordingly, it is difficult to quantitatively evaluate the reduction effect. The National Police Agency has quantified, by project category, CO_2 emissions reduction brought about by improved traffic signal control.(2) However, to further improve traffic signal control as a means of reducing CO_2 emissions in the future, we believe that a detailed quantification of CO_2 emissions reduction at each intersection is desirable. Therefore, with the aim of being widely recognized and used for the verification of the effect of improved traffic signal control, this paper reports on a model developed to calculate the amount of CO_2 emitted by vehicles traveling on the legs of intersections with traffic signal control, considering the traffic situation, vehicle class, and other factors.

2. Selecting a Model for CO_2 Emissions Calculation

A formula devised by Oguchi et al.(3) exists as a model for calculating the amount of CO_2 emitted by vehicles traveling on urban roads while starting and stopping repeatedly. The formula uses data on vehicles on short trips between starting and stopping. As connected cars have become popular, it is becoming increasingly possible to acquire information on short tripss by vehicles. At present, however, the acquired information is collected separately by businesses including automakers for their respective purposes and is not publicly available. Consequently, for the present, it is difficult to compile and use such information for the purpose described in this paper.

Meanwhile, Dohi et al.(4) present a method of calculating CO_2 emissions using emission intensities, which indicate CO_2 emissions per unit of travel distance, determined separately for representative vehicle classes and travel speeds. Data on mean speeds of vehicles traveling on roads divided into short sections are publicly available (for example, TomTom N.V.(5)). Using the method proposed by Dohi et al. as a starting point, this paper builds a model for calculating CO_2 emissions of vehicles traveling through an intersection using the following procedure.

(1) Prepare a table of CO_2 emission intensities by vehicle class-, fuel type-, and travel speed.

(2) Calculate emission intensities for different travel speeds on the legs based on the emission intensity table described in (1) and the percentages of vehicle classes traveling on the legs of the intersection subject to calculation.

(3) Calculate CO_2 emissions for the legs based on the emission intensities classified by travel speed described in (2), the traffic volumes on the legs, and the mean travel speeds on different sections of the legs.

Figure 1 illustrates these steps. Each of the steps will be explained in the following chapter and thereafter.

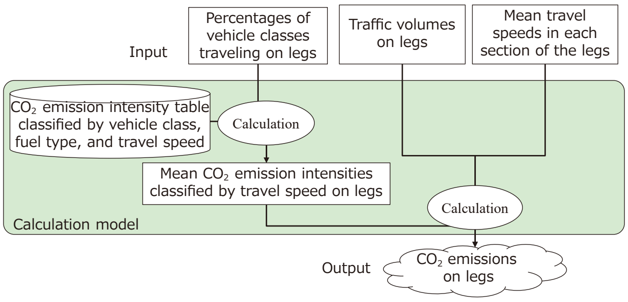

Fig. 1. Schematic diagram of CO_2 emissions calculation model

3. Preparing an Emission Intensity Table

In preparing a table of CO_2 emission intensities by vehicle class-, fuel type-, and travel speed, we looked for available data. We used CO_2 emission intensities available from the survey on vehicle emission intensities and total emissions[6] from Japan's Ministry of the Environment, considering that the data were released by a public organization and available to the general public. The survey calculated travel speed-specific emission intensities for each fuel type and vehicle class, classified by the year of enforcement of emission gas regulations. Weighted means of these emission intensities were taken with the weights being the percentages of vehicles of different compliant model years in order to prepare the vehicle class-, fuel-, and travel speed-specific table of emission intensities. The percentages of vehicles of different years of enforcement were calculated separately for passenger cars and trucks + buses, using data from the average vehicle age trend table classified by vehicle class[7] available from the Automobile Inspection & Registration Information Association. Although the data omits minicars, we applied it to minicars as well, assuming that they would be similar in vehicle age trend to the other vehicle classes.

In the data, the emission intensity for heavy vehicles is a value per ton of equivalent inertia weight.*1 Therefore, it is necessary to multiply the emission intensity by the equivalent inertia weight corresponding to the vehicle's weight including its occupants and cargo. The specifications for fuel consumption rate testing[8] give equivalent inertia weights for heavy vehicles as values close to the respective vehicle weights. Therefore, we assumed that the equivalent inertia weight of a heavy vehicle equaled the vehicle weight. Then, consulting the number of automobiles owned - by various categories[9] published by the Automobile Inspection & Registration Information Association, we collated the number of vehicles under ownership classified by gross vehicle weight*2 against the number of vehicles under ownership classified by loading capacity and matched the gross vehicle weights against loading capacities. Subsequently, assuming that vehicles would be fully loaded when traveling to the destination and be empty when returning, we determined the equivalent inertia weight by subtracting half the loading capacity from the gross vehicle weight. This assumption is believed to be valid as Dohi et al.[4] use half-loaded vehicle weights. Moreover, although the emission intensity data available from the Ministry of the Environment do not show details for either hybrid electric vehicles or electric vehicles, we considered it would be necessary to take hybrid electric vehicles into account on the basis of the numbers of low-emission vehicles under ownership classified by fuel type and vehicle class.[10] We calculated emission intensities for hybrid electric vehicles by converting from intensities for gasoline-driven passenger cars using the comparison of CO_2 emission intensities between hybrid electric vehicles and conventional vehicles reported by Dohi et al.[11] Table 1 presents the CO_2 emission intensities we prepared. Note that in the fuel column, G stands for gasoline, H for hybrid, and D for light oil; L, M, H1, and H2 stand for gross vehicle weights of 1.7 t or less, more than 1.7 t and up to 3.5 t, more than 3.5 t and up to 5 t, and more than 5 t, respectively.

Table 1. CO_2 emission intensities by vehicle class-, fuel type-, and travel speed (Unit: g/km)

Vehicle class	Fuel	Travel speed range (km/h)						
		3-5	5-10	10-15	15-25	25-40	40-60	60-80
Mini-passenger car	G	328	217	164	132	109	99	102
Passenger car	G	443	290	217	174	143	124	117
	H	149	101	85	73	68	69	73
	D	585	397	302	238	185	150	139
Mini truck	G	405	260	194	159	139	134	140
Truck/Bus	GL	463	304	228	182	149	132	132
	GM	702	444	323	251	203	177	173
	DM	721	447	319	245	195	168	158
	DH1	712	474	364	300	259	242	246
	DH2	1,109	795	642	546	469	417	394

4. Calculating Travel Speed-specific Emission Intensities for Legs

This chapter explains a procedure followed to calculate travel speed-specific emission intensities for the legs of an intersection. This calculation can be done by taking weighted means of the values for each vehicle class and fuel type listed in the vehicle class-, fuel type-, and travel speed-specific table of emission intensities described in the preceding chapter, with the weights being percentages by number of vehicles traveling on the legs for each vehicle class and fuel type. However, it is seldom possible to obtain data about percentages by number of vehicles for the same vehicle and fuel categories as those listed in the table described in the preceding chapter. It is highly likely that available data come with coarser vehicle classes. Consequently, it is necessary to estimate percentages by number of vehicles for each vehicle class and fuel type listed in the table (hereinafter referred to as the "vehicle classes in the table") based on percentages by number of vehicles for vehicle classes shown in available data (hereinafter referred to as the "vehicle classes in available data").

More specifically, first, each of the vehicle classes in the table is ascertained as to under which of the vehicle classes in the available data it falls. Next, it is assumed that, within one of the vehicle classes in the available data, the percentages of the individual vehicle classes in the table are equal to the percentages of owned vehicles for the individual vehicle classes in the table; under this assumption, the percentage of each of the vehicle classes in available data is divided according to the percentages of owned vehicles, and each dividend is assigned to the corresponding vehicle class in the table; in this way, the percentages of vehicles traveling on the legs are calculated for each of the vehicle classes in the table. Percentages of owned vehicles for the vehicle classes in the available data were calculated as shown in Table 2 based on the number of owned automobiles classified by vehicle class, fuel type, and initial registration year[12] published by the Automobile Inspection & Registration Information Association, and on the number of minicars under ownership[13] published by the Light Motor Vehicle Inspection Organization. Then, by obtaining weighted means of the emission intensities for the vehicle classes in the table, with the weights being the percentages of traveling vehicles for the vehicle classes in the table, we calculate travel speed-specific emission intensities for the legs.

Table 2. Percentages of Vehicles under Ownership for the Vehicle Classes in the Table

Vehicle class	Fuel	Percentage by number of vehicles under ownership (%)
Mini-passenger car	G	29
Passenger car	G	35
	H	13
	D	2
Mini truck	G	11
Truck/Bus	GL	1
	GM	2
	DM	2
	DH1	1
	DH2	4

5. Calculating CO_2 Emissions on Legs

The procedure described below is followed to determine CO_2 emissions on legs, using the travel speed-specific emission intensities calculated in the preceding chapter, the mean vehicle speeds in each section of the legs for different times of day, and the traffic volumes on the legs for different times of day. First, for each given time of day and each small section, using the travel speed-specific emission intensities calculated in the preceding chapter, what emission intensity corresponds to which time of day and to which vehicle travel speed is determined. Then, the result is multiplied by the length of each section to determine the CO_2 emissions per vehicle traveling in the section. Next, by adding up the CO_2 emissions per vehicle traveling in each section, it is possible to obtain the CO_2 emissions per vehicle on the legs at each given time of day. By multiplying the result by the traffic volume on the legs in the corresponding time of day and obtaining the sum with respect to all times of day, the CO_2 emissions on the legs can be determined. Figure 2 presents a calculation example.

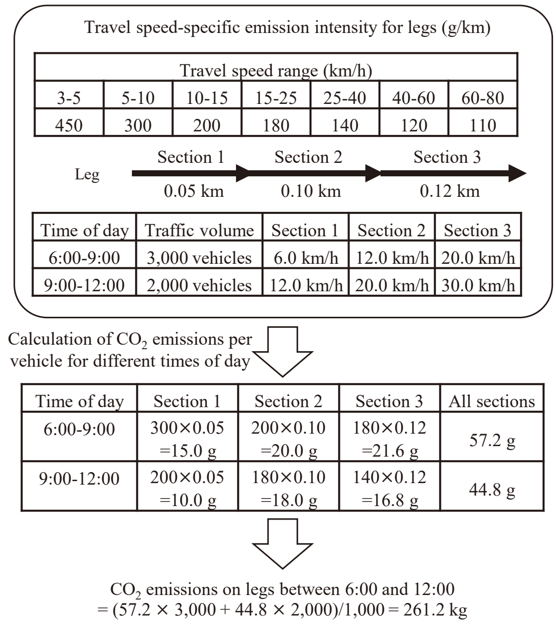

Fig. 2. Example of calculating CO_2 emissions on legs

6. Example of Evaluating Traffic Signal Control Improvements

Lastly, using the CO_2 emissions calculation model described in this paper, we evaluated the CO_2 emissions reduction effect actually brought about by improving traffic signal control. In 2019, the traffic signal control on the Hitomi-kaido intersection on Kanpachi-dori avenue was improved.[14] Focusing on this intersection, annual CO_2 emissions reduction was determined by calculating CO_2 emissions between 4:30 and 8:00 for seven weekdays each before the adjustment for regular operation and after the adjustment. We used traffic volume statistics from a fiscal 2020 survey conducted by the Metropolitan Police Department[15] for numbers of vehicles classified by vehicle class traveling on the legs; Seki et al.[14] for traffic volumes; and data provided by TomTom N.V.—a global traffic data vendor—for the section-specific mean travel speed. The traffic volume statistics of the Metropolitan Police Department divide motor vehicles into four vehicle classes:

Table 3. Correspondence between Four Vehicle Classes in Traffic Volume Statistics and Vehicle Classes in the Table

Vehicle class	Fuel	Large passenger cars	Large trucks	Passenger cars	Trucks
Mini-passenger car	G			✓	
Passenger car	G			✓	
	H			✓	
	D			✓	
Mini truck	G				✓
Truck/Bus	GL	✓			✓
	GM	✓			✓
	DM	✓			✓
	DH1	✓			✓
	DH2	✓	✓		

large passenger cars, large trucks, passenger cars, and trucks. According to the definitions of these classes, we established correspondence between these vehicles classes and the vehicle classes in the table, as illustrated in Table 3.

Table 4 lists the averages of the calculated CO_2 emissions and CO_2 emissions reduction for the duration between 4:30 and 8:00 on days before and after the adjustment. Let us assume that it is an average weekday reduction and the same effect takes place 240 days a year; then, the CO_2 emissions reduction effect enabled by improved traffic signal control is estimated at 6.7 t a year for the Hitomi-kaido intersection on Kanpachi-dori avenue alone.

Table 4. CO_2 Emissions Reduction Calculation Results (Unit: kg)

Before adjustment	After adjustment	Reduction
3,359	3,331	28

7. Conclusion

With the aim of gaining wide recognition and of being put to wide use, this paper created a model of calculating CO_2 emissions on the legs of intersections taking into account travel speeds in each road section and class breakdown of traveling vehicles, and demonstrated that the model can be applied to evaluate actual CO_2 emissions reduction effects brought about by improved traffic signal control. In applying this model, it is desirable to update, as appropriate, the vehicle class-, fuel type-, and travel speed-specific table of emission intensities. For that purpose, it is desirable to gain cooperation from automakers in taking measurement data from new vehicle models. We would be pleased if this paper provided a starting point in considering building a framework for gaining such cooperation. Regarding new vehicles released to the market in the future, it is certain that the proportion of electric vehicles and other zero-emission vehicles will increase. However, it will take some time before vehicles traveling on roads are mostly zero-emission vehicles; for the time being, many conventional gasoline- and diesel-powered vehicles will be traveling; therefore, we believe that it is important to address the issue of CO_2 emissions reduction by improved traffic signal control and other similar means. Sumitomo Electric Industries, Ltd. would like to make contributions in tackling this challenge.

Technical Terms

*1 Equivalent inertia weight: The weight determined by the vehicle weight plus the rotary inertia force exerted by the engine, the drive system, and other rotary parts as an apparent increment of vehicle weight, viewing the rotary inertia force as a resistance to vehicle acceleration

*2 Gross vehicle weight: The weight determined by adding the vehicle weight, the weight corresponding to the riding capacity, and the carrying capacity.

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