TRAFFIC SIGNAL CONTROL FOR REDUCING VEHICLE CARBON DIOXIDE EMISSIONS ON AN URBAN ROAD NETWORK

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ABSTRACT

The level of carbon-dioxide (CO_2) emissions, particularly of those caused by motor traffic, has been increasing year after year in Japan. This paper proposes a traffic signal control method to reduce vehicle CO_2 emissions based on understanding this background. First, a traffic flow simulation model was applied to obtain wide area traffic flows, so that a simulator could be established to obtain an estimated figure of CO_2 emissions generated by traveling vehicles while considering the state of each vehicle. An analysis of relations between CO_2 emissions and both of delay time and the number of stops at intersections was conducted with the simulator, which resulted in a proposal of a new traffic signal control method being expected to help us reach our target to reduce CO_2 emissions. Then, simulation experiments were conducted on major arterial roads in Kawasaki City to verify the new method, resulting in a roughly 7 % reduction of CO_2 emissions from the levels of the exhaust gas reduced by the current traffic signal control method. As a result, the authors confirmed the new method to be effective.

INTRODUCTION

Total carbon-dioxide emissions are 1.24 billion tons in Japan, which is a 10.5 percent increase from 1990 levels of CO_2 emissions. Among others, 0.26 billion tons, which is equal to more than 20 percent of the total CO_2 emissions, is generated by transport industry, showing a 20.6% growth from the 1990 levels. Motor traffic, in particular, has caused more than 80 percent of the total emissions generated by the transport industry. Therefore, it is necessary to improve vehicles and take various measures to reduce CO_2 emissions for prevention of global warming from now on. Though Traffic Control Centers (TCC) have managed urban traffic by taking many steps to smoothen traffic flows, it is now required for the centers to take early measures for environmental protection to overcome such a severe condition. To achieve this, it is necessary to estimate current levels of actual CO_2 emissions generated by motor traffic. Besides, new traffic-related steps have to be planned and taken to evaluate estimated impacts on reducing the emissions when they are introduced. Under the aforementioned background, this paper describes a traffic signal control method, which has shown its good effectiveness at the existing TCC, and proposes a control method to reduce CO_2 emissions.

Procedures for this paper are as described below. First of all, a CO_2 emission-estimation simulator is to be established to estimate CO_2 emissions generated by motor vehicles on arterial roadways under the traffic control. This system combines a traffic flow simulation model and the CO_2 emission-estimation model, to take into account wide area traffic flows based on the traffic flow simulation model and estimate a state of each traveling vehicle. In addition, such data are then applied to the emission-estimation model as an input value for estimating CO_2 emissions. At the same time, we analyze a correlation of the CO_2 emissions with both of delay time and the number of times a vehicle came to a halt at an intersection, which were outputted from the traffic flow simulation model. Then, based on the results, we suggest a traffic signal control method for reducing CO_2 emissions. Finally, a simulation test is to be conducted on major arterial roadways in Kawasaki City to verify the effectiveness of the proposed method as to levels of reduced CO_2 emissions.

SIMULATOR FOR ESTIMATING VEHICLE CO_2 EMISSIONS

A CO_2 emission-estimation simulator, which consists of a traffic flow simulation model and CO_2 emission-estimation model, has the following features: Figure 1 illustrates the simulator.

(a) Being able to apply a macroscopic model of traffic flow simulation,

(b) Being able to estimate states of traveling vehicles,

(c) Being able to estimate CO_2 emissions every five minutes per link, and

(d) Being connectable with multiple traffic signal control methods.

MACROSCOPIC TRAFFIC FLOW MODEL

It is necessary to recreate wide area traffic flows since CO_2 emissions generated by motor traffic are estimated based on data collected from major arterial roadways being under traffic control. Hence, a macroscopic traffic flow simulation model is applied to enable to transact traffic flows on wide area urban streets. We employed AVENUE [1] (an Advanced & Visual Evaluator for road Networks in Urban arEas) as a macroscopic simulation model of traffic flows for this research. AVENUE is packaged based on a time scanning system, of which minimum unit of time is one second, to recreate a traffic state for every scanning interval. Also, it employs hybrid block density system as a traffic flow simulation model. The system divides each lane of a roadway into subsections of 10-20 meters long called “Blocks,” then it obtains a value of traffic volume to be shifted to other subsections based on traffic flow characteristics specified for every block. The hybrid block density system enables us to deal with individual vehicles separately, resulting in an ability to utilize attributes of each vehicle classification. Owing to this, AVENUE has capabilities to package various traffic measures or to combine a function to allow drivers to select or change lanes, and is able to take into account a location and a speed of each traveling vehicle for every scanning interval due to its function to deal with individual vehicle behaviors. Thus, it is able to obtain traveled path as well as travel time of each vehicle. Oneyama et al. [3] have proposed a method, which classifies a state of a traveling vehicle into halting, accelerating, decelerating, a fixed-speed traveling based on a linear approximation of a travel locus, then estimates sections the traveled in the classified state. This paper employs this method to determine the state of each traveling vehicle and to estimate sections traveled in every state.

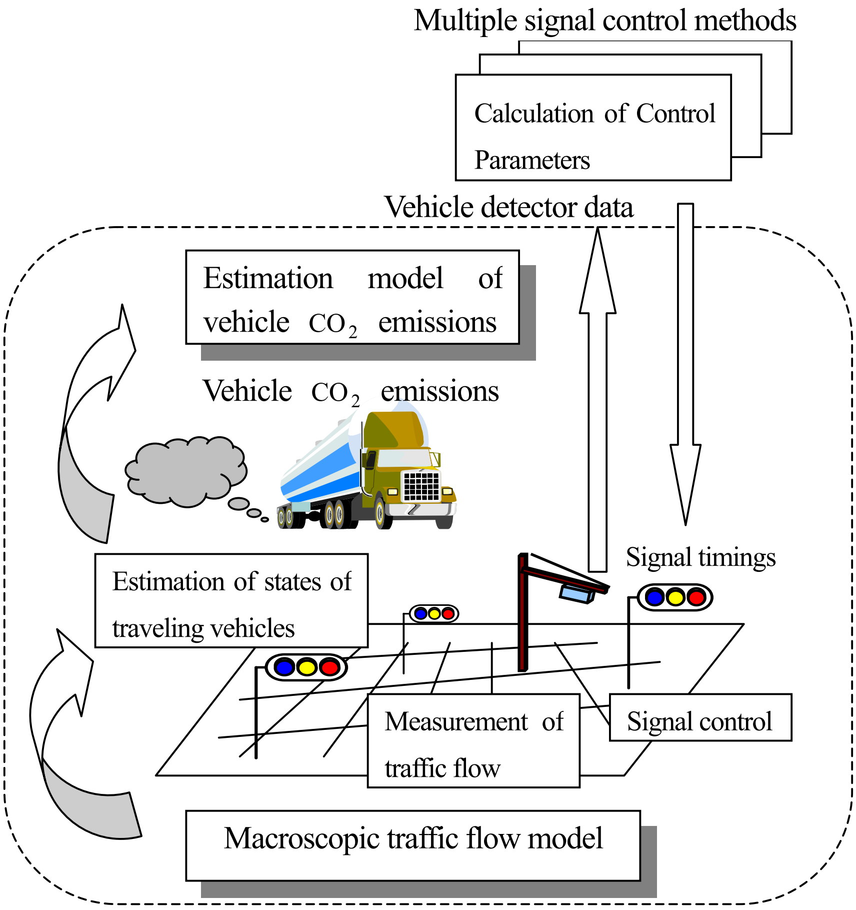

Figure 1 Vehicle CO_2 Emissions Estimation Simulator

VEHICLE CO_2 EMISSIONS EATIMATION MODEL

Since CO_2 emissions are to be estimated based on a state of each traveling vehicle in this study, the authors introduce a CO_2 emission-estimation model to describe a relationship between CO_2 emissions and a condition of vehicle motion. The model proposed by Oguchi et al. [2] is employed for this paper for the estimation. This model estimates CO_2 emissions as represented in the formula below:

$$E = 0.3K_c T + 0.028K_c L + 0.056K_c \sum_k \delta_k (v_k^2 - v_{k-1}^2) \qquad (1)$$

where,

E: CO_2 emissions [kg],

K_c: coefficient,

T: travel time in a link [sec],

L: length of a link [m], and

v_k: velocity in time k [m/sec].

Also, δ_k would be 1 when a vehicle is accelerating during time k, otherwise it would be 0.

ESTIMATION OF VEHICLE CO_2 EMISSIONS

CO_2 emissions generated by an individual vehicle are to be derived by inputting a travel speed, state and time of every vehicle, which are outputted through AVENUE, to the aforementioned emission-estimation model. The simulator aggregates the estimated figures every five minutes per a link (sections between signalized intersections). It then sums up such figures to obtain an estimated figure of CO_2 emissions generated on an entire road network, to conduct an evaluation in respect of introducing traffic measures.

CONNECTING WITH TRAFFIC SIGNAL CONTROL METHODS

Since this research applies to many different signal control methods as will de described shortly, a function to create control parameters (i.e., cycle length, splits and offsets) required to control traffic lights is to be an external process toward AVENUE. Thus, data on signal timing of each traffic signal is to be determined externally, then, given to AVENUE. On the contrary, as similar as the case under the current traffic control method, traffic flows are to be monitored by installing vehicle detectors on AVENUE. Each vehicle detector measures traffic volume and time occupancy, which is to be provided for an external process to calculate the control parameters. With that, a simulated traffic signal control, including external processes, is realized.

TRAFFIC SIGNAL CONTROL

APPROACH

It is necessary to determine appropriate evaluation indexes as well as to create control parameters to optimize them for controlling traffic signals to reduce CO_2 emissions generated in a wide area under traffic control. There are two approaches to calculate the indexes. One is to adopt the summation of figures of CO_2 emissions generated by individual vehicles as the evaluation index. Another is to educe a traffic index being highly interrelated with CO_2 emissions to employ it as an alternative index to CO_2 emissions.

The former approach employs equation (1), yet it requires judgment whether each vehicle is in an accelerating state or not, based on its trajectory. Since the approach would cover wide area traffic flows causing a tremendous number of vehicles to be dealt with, it takes considerable time to process states of traveling vehicles. On the contrary, in the latter method, an attempt is made to find a traffic index which is highly interrelated with aggregated CO_2 emissions on all signal controlled routes, to determine optimal control parameters by applying CO_2 emissions as an alternative index. Though this approach does not always create control parameters to minimize the emissions, the approach is expected to calculate the control parameters to nearly minimize them. Since the traffic control center requires real time signal control, the control parameters covering a wide area have to be computed in a short time. Taking the circumstances on limitations on computation resources into consideration, this paper adopted the latter approach.

CORRELATION ANALYSIS OF CO_2 EMMISIONS WITH TRAFFIC INDEX

Evaluation indexes for traffic signal control include delay time or the number of times a vehicle stopped at intersections. This section analyzes a correlation of CO_2 emissions with the indexes through carrying out a simulation. Based on the emission-estimation simulator described earlier, the simulation was conducted on major routes including Sangyo-doro and national road Route 1 and 15 in southern area of Kawasaki City. In the simulation, time series traffic volume generated on the routes was given to the simulator to output the levels of emissions generated on each link in every five minutes. Then, the results were aggregated to obtain a time series for each of the aforementioned routes. Delay time and the number of stops at intersections were outputted as well to be totaled per link for every five minutes, as is the case with the levels of emissions.

Table 1 indicates the analysis results of the simulation. Data was aggregated per route. The table shows correlation coefficients of emissions with delay time and the number of stops in five minutes.

Table 1 Correlation Coefficients of CO_2 Emissions and Traffic Indexes

Routes	Delay time	Number of stops
Sangyo-doro	0.96	0.98
National Road Route 1	0.94	0.96
National Road Route 15	0.94	0.98

The simulation test results provided high correlation coefficients, indicating positive correlation of both indexes with CO_2 emissions on every route. The obtained coefficients indicated that the number of times a vehicle stopped had a particularly high correlation with the levels of CO_2 emissions. Hence, it is expected that decreased traffic indexes would cause to reduced CO_2 emissions. The following subsection is devoted to propose a signal control systems employing such indexes as delay time and the number of stops.

PERFORMANCE INDEX FOR SIGNAL CONTROL

A linear sum of delay time and the number of times a vehicle made a stop is applied in this paper as an evaluation index for reducing CO_2 emissions. An evaluation index p_i of link i in an urban road network is determined as the formula below:

$$p_i = \alpha_i d_i + \beta_i s_i \quad (2)$$

where,

d_i denotes delay time in link i,

s_i denotes the number of stopping in link i,

α_i and β_i denote weight coefficients.

Therefore, performance index P of the entire urban road network is represented as:

$$P = \sum_i p_i = \sum_i (\alpha_i d_i + \beta_i s_i) \quad (3)$$

OPTIMIZATION OF SIGNAL CONTROL BASED ON META-HEURISTICS

In optimizing the control parameters, it is required to compute an optimal value of the traffic index, for a combination of cycle length, splits and offsets in an entire wide area. In this case, since a function to represent the index is not given explicitly, it is necessary to carry out a search to determine an optimal solution. This paper employs meta-heuristics, including random search and genetic algorithm, for an effective online and real time search for a solution. Additionally, the number of variations is to be estimated to enhance convergence of a solution [4-5].

EVALATION OF SIGNAL CONTROL BASED ON ESTIMATION OF CO_2 EMISSIONS

Signal timing data are to be created based on the control parameters obtained by the aforementioned procedures, to provide a control command for traffic signals in a traffic control area. On the contrary, when the CO_2 emission-estimation simulator is assumed to be a virtual field, it would be able to estimate CO_2 emissions by providing the same command data for simulated traffic signals, which enables evaluation of the aforementioned signal control system. Besides, the simulator would be able to estimate the levels of CO_2 emissions generated under the existing control systems, e.g., pattern selection control, by arranging input values to the simulator. In this way, it would be possible to verify an applied signal control method, as compared with the current control method, regarding the levels of reduced CO_2 emissions.

EXPERIMENTS

EXPERIMENT PROCEDURE

A simulation test was conducted in a wide area, which is now under control of the TCC, to verify the effectiveness of the signal control system proposed in this paper. The test area covered the aforementioned three major arterial roads, which were objects of the correlation analysis. Traffic signals in the area are currently controlled via Kawasaki Traffic Control Center, employing a pattern selection method to specify the control parameters. Assuming that the CO_2 emission-estimation simulator was a virtual field, this experiment treated both of the proposed system and the pattern selection method as external processes. In this manner, each method created the control parameters based on vehicle detector data obtained by the simulator, determined signal timings while taking into account influence from offset transition and others, then gave the control command data to the simulator. Also, simulated time series traffic was generated from 5:00 to 19:00 on weekdays to try these two different signal control methods. Then, the estimated CO_2 emissions from the simulation output under the two methods were compared.

RESULTS OF EXPERIMENTS

Figure 2 and 3 show the test results. Figure 2 indicates a comparison between the levels of CO_2 emissions of the different signal control systems. By dividing the test hours into three time groups, Figure 3 shows a time-of-day comparison of CO_2 emissions. Every value in the both figures is an estimated figure for five minutes, and a corresponding value for a distance of one kilometer.

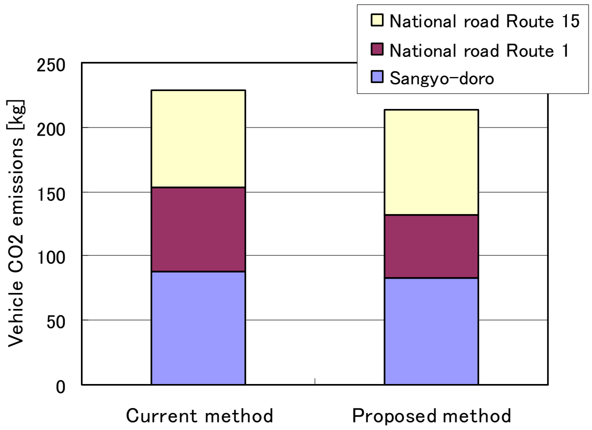

Figure 2 Comparison of Estimated CO_2 Emissions between Two Methods

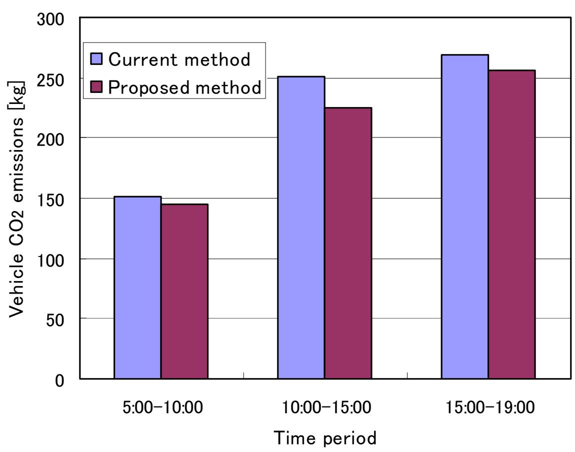

Figure 3 Comparison of Estimated CO_2 Emissions in Each Time Period

Based on these results, the authors confirmed the effectiveness of the proposed method since it was able to reduce the levels of CO_2 emissions by nearly seven percent as compared with the existing one. Also, a route comparison revealed that the new method had a great impact, particularly on Route 1, with the figure of some twenty-four percent reduction in CO_2 emissions. On the contrary, concerning time-of-day comparison of CO_2 emissions, each route showed different patterns of fluctuation in traffic flows depending on time of day, which resulted in different levels of CO_2 emissions. Yet, we revealed that the levels of CO_2 emissions were greatest during a period of time from 10:00 to 15:00 as far as the entire three routes are concerned. Besides, the highest improvement, which was more than a ten percent reduction, was observed during the same period of time.

CONCLUSIONS

The authors constructed a CO_2 emission-estimation simulator for this research by utilizing a traffic flow simulation model, AVENUE, to propose a signal control method intended to reduce CO_2 emissions. Also, we made a correlation analysis of CO_2 emissions with delay time and the number of stops based on the simulator. The results revealed a strong correlation of CO_2 emissions with the two factors. We then applied meta-heuristics to establish a system to control traffic signals through the optimization of control parameters while employing delay time and the number of stops as the indexes. In addition, a wide area simulation experiment was conducted in the southern area of Kawasaki City to confirm reduction in the levels of CO_2 emissions achieved by the proposed method. In future research, the authors plan on further improvements for an online and real time system to be packaged.

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