Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

Method of estimating the change in life cycle CO_2 due to transport system development incorporating micro-traffic flow simulation

Naoki SHIBAHARA[a]*, Ryoko MORIMOTO[b], Nozomi KUDO[c], Hirokazu KATO[d], Shingo MANO[e], Yoshitsugu HAYASHI[a]

[a]*Chubu university, 1200 Matsumoto-cho, Kasugai, Aichi 487-8501, Japan*
[b]*None*
[c]*National Traffic Safety and Environment Laboratory, 7-42-27 Jindaiji-Higashimachi, Chofu, Tokyo 182-0012, Japan*
[d]*Nagoya university, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan*
[e] *Kyoto Station Building Development Co.,Ltd., 1-12-15-101 Senrioka-higashi, Settsu, Osaka 566-0011, Japan*

Abstract

In this research, a method of estimating the system overall life cycle CO_2 emissions including vehicle traveling, infrastructure construction, and new manufacture of vehicles is constructed in order to comprehensively evaluate the change in CO_2 emissions associated with transport system development. In particular, congestion of automobiles due to traffic signals and turning left and right, etc., and the detailed driving behavior of vehicles including mixing of light rail transit (LRT) and automobiles on the road can be analyzed by micro-traffic flow simulation. A framework is presented for the introduction of LRT that enables conversion from parallel fixed route buses and the increase in congestion of automobiles due to the reduction in the number of traffic lanes to be taken into consideration. As a result of application of this estimation method to a case study, the effect of automobile congestion brought about by the reduction in the number of traffic lanes and the introduction of LRT priority signals on CO_2 emissions was quantitatively determined.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: acceleration and deceleration, life cycle CO_2, LRT, microscopic traffic simulation model, modal shift

1. Introduction

In the urban traffic field, a modal shift from private transport to public transport is considered to be effective for energy efficiency and reduction in CO_2 emissions. In order to evaluate the effect of a modal shift, in addition to the

* Corresponding author. Tel.: +81-568-51-4595; fax: +81-568-51-1495.
E-mail address: shibahara@isc.chubu.ac.jp

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY

transport efficiency aspect of public transport, constructing a method of estimating the overall system life cycle CO_2 emissions and evaluating the change in CO_2 emissions associated with a traffic system development is an important aspect[1)-5)].

In this research, the introduction of LRT is taken as a case study, and a methodology is constructed for evaluating the life cycle environmental load before and after development, taking into consideration the driving behavior of vehicles expressed using micro-traffic flow simulation. Vehicles traveling on the road network near the LRT line were included in the scope of evaluation, and the ripple effect of the development on the surroundings was evaluated. The factors affecting emissions originating from vehicles were analyzed by investigating in detail the driving behavior of 1 vehicle and the driving mode.

2. Method of Estimating CO_2 Emissions

2.1. *Setting the scope of evaluation*

In this research, the life cycle CO_2 emissions were estimated for a project to replace a fixed route bus with a new LRT as a case study. In addition to the fixed route bus and LRT traffic systems, automobiles were included in the scope of evaluation. LRT can be considered to be a system consisting of infrastructure (main structure such as tracks, etc., and ancillary structures such as stops, etc.) and vehicles. On the other hand, for conventionally operated fixed route buses the infrastructure (roads, stops, etc.) already exists, so it is not included in the estimate, so the CO_2 is evaluated for vehicle manufacture, renewal, and operation. The methodology described in this research can also be applied in the same way to the development of modes of transport other than LRT, so for reference an example of BRT is shown in Fig. 1 and described in the next section.

It was assumed that the life time of the system is 60 years for both LRT and fixed route bus, and it was assumed that vehicles are renewed every 30 years for the LRT and every 10 years for fixed route buses. Also, the change in the environmental load originating from automobiles (passenger cars, trucks) whose traffic flow is changed by the development of the LRT and elimination of the fixed route buses was taken into consideration. The type of environment load considered was CO_2. The scope of evaluation is shown in Fig. 1. In this research, the life cycle CO_2 of LRT and fixed route buses is referred to as SyLC-CO_2 (System Life Cycle CO_2), and the extended life cycle CO_2 that includes automobiles is referred to as ELC-CO_2 (Extended Life Cycle CO_2).

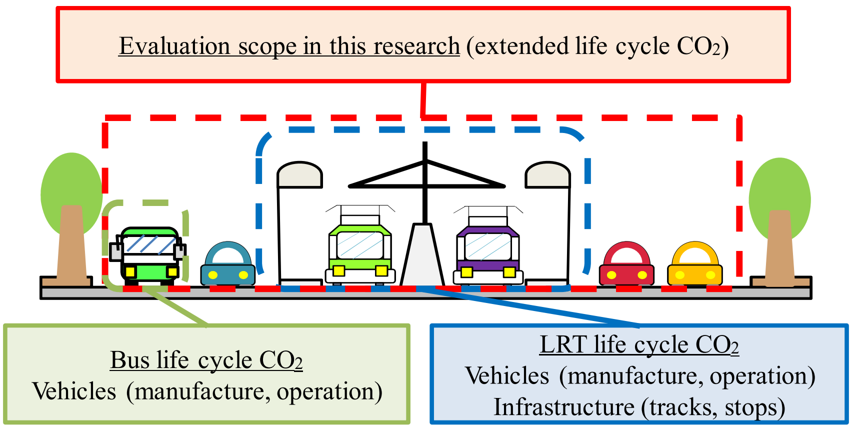

Fig. 1. Evaluation scope setting

The flow of estimation is shown in Fig. 2. CO_2 emission factors are used for each of the constituent elements of fixed route buses, LRT vehicles, and infrastructure. The CO_2 originating from fixed route buses, LRT, and automobiles was obtained from micro-traffic flow simulation. The details are described from the next section onwards. Also, in research carried out in the past, a method using the fuel and electricity consumption of buses or LRT, or a method of obtaining the CO_2 from operation of automobiles from, for example, fuel consumption equations using the average traveling speed as an explanatory variable by Dohi et al.[6], have been frequently used. However, in this research, micro-traffic flow simulation was used as an alternative to these methods.

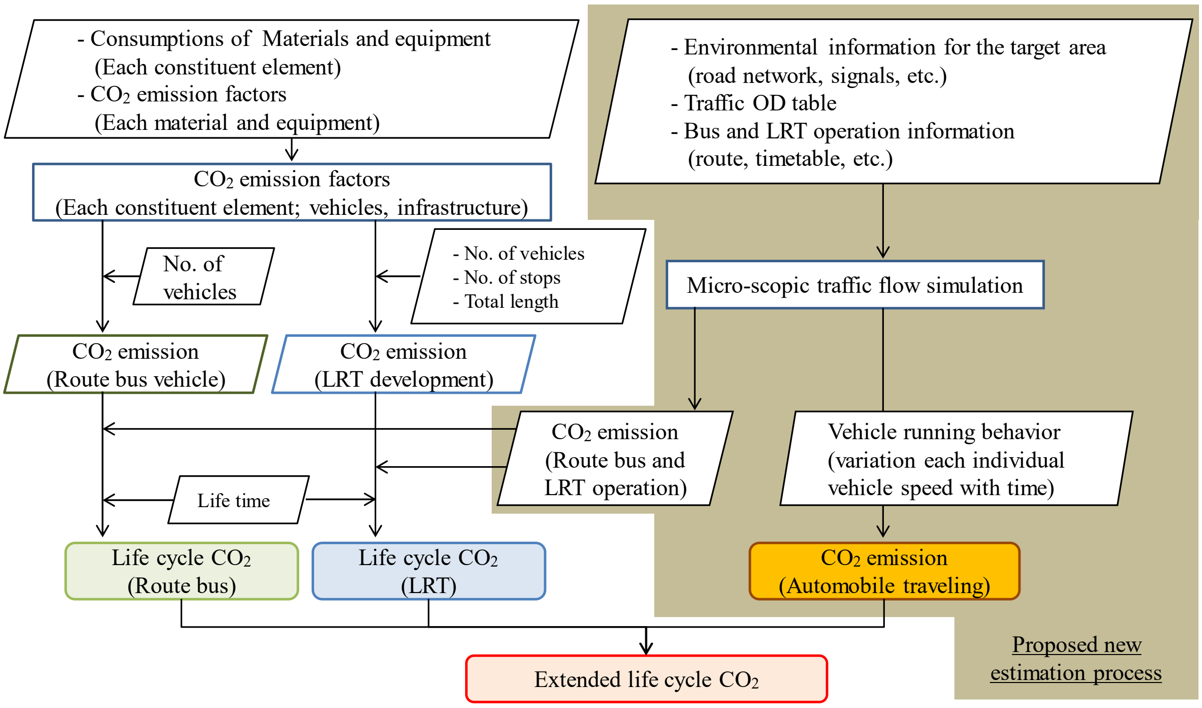

Fig. 2. Life cycle CO_2 estimation flow

2.2. *Method of estimation for vehicle manufacture, infrastructure construction and maintenance stages*

For both the LRT and the fixed route bus systems, the CO_2 emissions are obtained for vehicle manufacture and for infrastructure (LRT only). Estimation values from previous research[7] were used for vehicle manufacture. LRT infrastructure construction is broadly divided into tracks and stops, and CO_2 emission factors for each developed in previous research[7] were used. LRT infrastructure maintenance and repair was assumed to be carried out every year, and rails were assumed to be replaced once every 20 years. Table 1 summarizes these estimation setting values.

Table 1. CO_2 emission factors for LRT and fixed route bus[7]

System	Constituent element	Stage	CO_2 emission factor
LRT	Vehicles	a) Manufacture [t-CO_2/train]	39.3
	Infrastructure	b) Tracks [t-CO_2/km]	1,070
		c) Stops [t-CO_2/stop]	14.4
		d) Maintenance and repair [t-CO_2/year]	4
Fixed route bus	Vehicles	e) Manufacture [t-CO_2/vehicle]	36.4
(Reference) BRT	Vehicles	Manufacture [t-CO_2/train]	39.3
	Infrastructure	Stops [t-CO_2/stop]	14.4

Also, instead of introducing LRT tracks, if BRT is developed using 1 lane as a dedicated bus lane, the CO_2 emission factors required for estimation are also shown in Table 1. Installation of compartment lines is small compared with other constituent elements, so it is omitted.

2.3. *Method of estimation in the vehicle operation stage using micro-traffic flow simulation*

In this research, an urban traffic simulator developed by the National Traffic Safety and Environment Laboratory was used to obtain the CO_2 emissions for operation of conventional fixed route buses, automobiles, and newly installed LRT. An outline of the simulator is shown in Table 2, and an example of simulation execution display screen is shown in Fig. 3. This simulator is capable of calculating the effect on automobile traffic of introduction of LRT by setting the LRT route on a map, and carrying out mock operation in parallel with operation of road traffic (automobiles, buses). LRT is given a vehicle performance curve, a limiting velocity, and a curve passage velocity, and obtain the energy consumption from line power and regenerative power when operating in accordance with the traffic signals. For automobiles, micro-traffic flow simulation was carried out based on a vehicle to vehicle tracking behavior model, for traveling on the road network with a predetermined destination with each individual vehicle complying with the signals.

Therefore, it was possible to reproduce running modes such as accelerating, decelerating, and stopping (idling), and to obtain positional data for each vehicle every 0.5 seconds. Ordinary gasoline automobiles and large bus and diesel vehicles are handled by this simulator, and from each vehicle the CO_2 emissions were calculated by calculating the instantaneous fuel consumption in accordance with the running mode, and multiplying it by the CO_2 emission coefficients determined by the Ministry of the Environment.

Table 2. Outline of the urban traffic simulator

	Function	Setting parameters
Road	Network configured from intersection nodes	Simulation target area
Signal	Reproduction of automobile traffic in accordance with signals	Cycle length, offset, also simulates green arrow
Automobile	Route assumed for each individual vehicle Drives in accordance with the speed of the automobile in front Simulates multiple lanes in the same direction	Traffic OD table from point of origin to point of disappearance Distance between vehicles No. of lanes
Other traffic	Simultaneous running with LRT Simultaneous running with buses	Route, vehicle parameters Route, timetable, bus stops

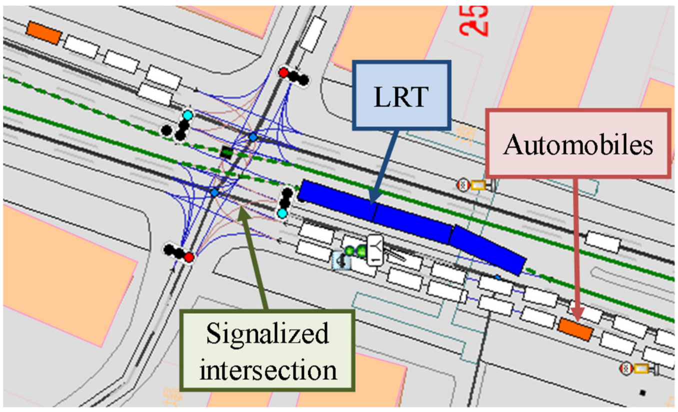

Fig. 3. Example of simulation execution display screen

3. Estimation of CO_2 emissions in the case study

3.1. *Outline of the case study*

The LRT introduction scheme that was the subject of the evaluation was in a government ordinance city in the Tokai region that was actually planned around the central station. An outline of the scheme is shown in Table 3 and in Fig. 4. It was envisaged that as a result of introduction of the LRT the fixed route buses that formerly operated on the same route would be eliminated, and that the users would all convert to the LRT. With the installation of dedicated tracks the number of lanes on which automobiles can run is reduced. Also here conversion of automobile traffic running on the route alongside the LRT is not taken into consideration. In the actual scheme, besides the reduction in the number of lanes on the roads on which the LRT is introduced, modification of the road network is not envisaged. In this research, the estimates were carried out in accordance with this concept, and modifications or other postulated concepts were not considered.

Table 3. LRT scheme and existing bus route evaluated

	Fixed route bus (existing)	LRT (scheme)
Vehicle weight [t/vehicle (train)]	10.7	25.0
No. operations [No./day]	450	320
Scheduled speed [km/h]	10.2	16.8
No. stops [No.]	50	36
Total length [km]	14.5	14.5
No. transported [passengers/day]	27,000	27,000
No. vehicles	15 [No.]	20 [trains]
Capacity [passengers]	80	150

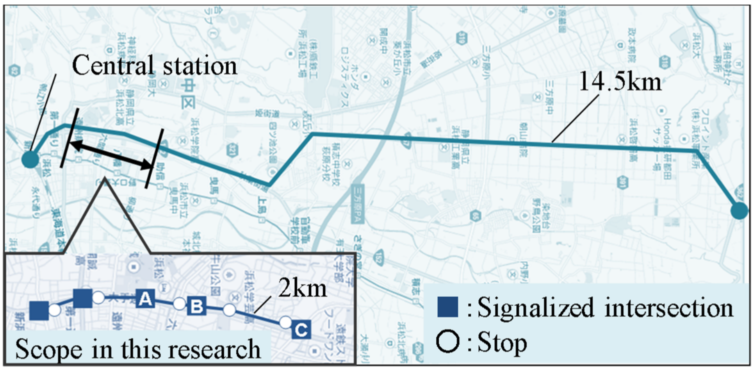

Fig. 4 Outline of simulation area

3.2. *Micro-traffic flow simulation setting conditions*

The automobile driving conditions were reproduced using the traffic volumes in the simulation area at each intersections going straight, turning left, and turning right, based on the Ministry of Land, Infrastructure, Transport and Tourism's 2005 General Road Traffic Survey Data. The simulation setting conditions are shown in Table 4.

The estimation by simulation was carried out in 1 hour units. For each 1 hour time band in 0 to 24 hours, traffic volumes were applied, simulation was carried out, and the CO_2 emissions were estimated, with reference to the changes in the trip aggregated distribution for each aggregated time in the PT survey. The estimated results for each hour were added to calculate the CO_2 emissions in 1 day, and converted to a life time of 60 years.

Table 4. Simulation setting conditions

LRT route	Dedicated tracks were installed on a normal national road having 3 lanes (in part 2 lanes) per direction, connecting the central station of a certain government ordinance city to the outskirts
OD data	2005 Road Traffic Census: Survey of traffic volumes at the main intersections
Traffic signals	Application of Public Transportation Priority System (PTPS) to the LRT
Calculation time	1 hour (repeated for each 1 hour time band from 0 to 24 hours)

3.3. *Estimated ELC-CO_2 result for the whole traffic network*

The estimated ELC-CO_2 result for the whole traffic network is shown in Fig. 5. Although the CO_2 emissions originating from infrastructure are higher for LRT development compared with the conventional case (fixed route bus), the CO_2 from operation is smaller, so the SyLC-CO_2 is reduced, although by a small amount. However, the emissions due to the surrounding traffic flow (CO_2 emissions originating from driving automobiles) increased by 528 kt-CO_2/60 years, and if this amount is included the result obtained is that the ELC-CO_2 increases. In other words, by just converting bus users to LRT users, the ELC-CO_2 increases for the whole traffic network.

This estimate incorporating micro-traffic flow simulation takes into consideration the change in the driving situation (reduction of speeds due to congestion, etc.) for automobiles traveling alongside the LRT, associated with the reduction in the number of lanes due to installation of the dedicated tracks and the introduction of LRT priority signals. However, it is not possible to know how development of the LRT affects automobiles by just comparing the change in total ELC-CO_2. Therefore, in the next section the driving behavior of the automobiles is analyzed in detail, to verify how the surrounding traffic congestion or the effect of the LRT priority signal is expressed in the micro-traffic flow simulation, and how the ELC-CO_2 is affected.

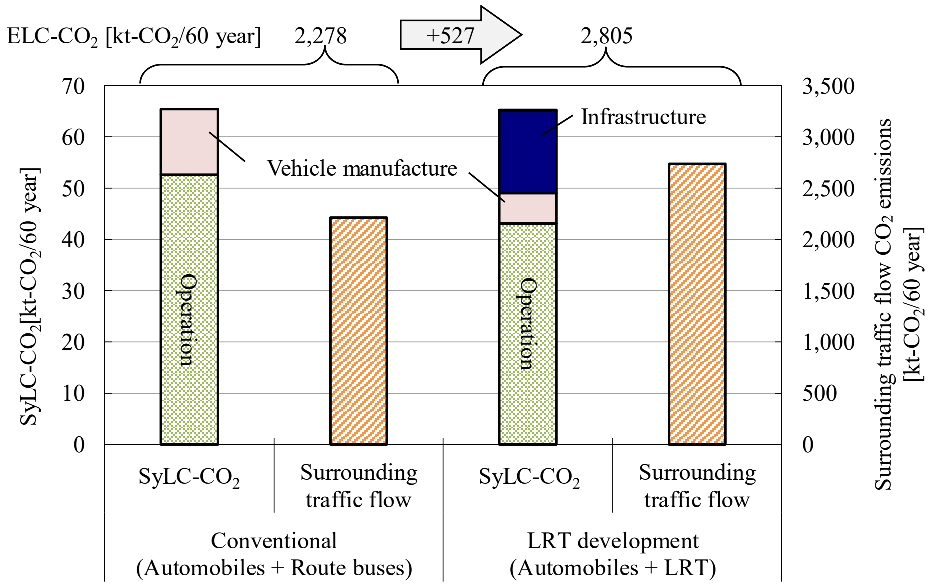

Fig. 5. CO_2 estimation results for the whole traffic network

4. Detailed Analysis of Driving Behavior

4.1. *Analysis of the factors affecting CO_2 emissions of automobiles during operation*

The CO_2 from automobile operation in 1 hour and the average traveling speed obtained from the micro-traffic flow simulation are shown in Table 5. Here the CO_2 emissions are the total CO_2 emissions due to automobile operation in 1 hour including the surrounding traffic flow. In the area under consideration, congestion occurs near one intersections going towards the central station only. Therefore, the analysis of automobiles was carried out separately for the 2 directions. In the direction away from the central station in the LRT development, congestion occurs outside the area under consideration, and the total number of vehicles traveling is reduced. As a result, the total CO_2 emissions in 1 hour is small, even though the CO_2 emissions per vehicle-km is large.

Table 5. Estimation results for automobile CO_2 emissions and average traveling speed in the area under consideration based on the simulation

		CO_2 emissions		Average traveling speed
		[kg-CO_2/hour]	[kg-CO_2/vehicle-km]	[km/h]
Towards central station	Conventional	188	0.094	18.5
	LRT development	180	0.092	14.7
Away from central station	Conventional	173	0.083	24.4
	LRT development	113	0.088	20.9

In Section 3, the result that CO_2 emissions for the whole traffic network increased due to the LRT development was obtained, but in the estimate for this part of the area the CO_2 emissions for the LRT development were smaller compared with the conventional case in both directions. The area under consideration in this section is a city center area close to the central station where the traffic volume is high, so it is considered that the road conditions are greatly affected by the introduction of LRT. Therefore, there is a possibility that the change in the automobile driving circumstances is different from the trend shown in Section 3 which includes the outskirts. In particular, it is considered that the effect of introduction of LRT priority signals is greater in the city center area where there is congestion at the intersections. Moreover, although the average traveling speed reduced by about 3 km/h in both directions, the CO_2 emissions per vehicle-km reduced in the direction away from the central station. It is known that in the speed range on normal roads, reducing the average traveling speed increases the CO_2 emissions, which is different from this result.

As a result of road congestion associated with the LRT development, the speeds of both the LRT and the automobiles traveling alongside the LRT are reduced, but due to the effect of the LRT priority signal an increase in vehicles traveling smoothly is seen (the proportion of acceleration and deceleration is shorter and the proportion at constant speed is longer). As a result, CO_2 emissions are reduced by the development of the LRT.

4.2. *Discussion regarding the necessity of traffic flow simulation*

In the previous section it was shown that even though the amount of change in the average traveling speed associated with the LRT development was the same in both directions, the details of the traveling modes were different. Also, a case was seen in which CO_2 emissions did not increase even though the average traveling speed was reduced. The method of estimation using fuel consumption equations with the average traveling speed as an explanatory variable in accordance with Dohi et al.[6)], for example, is frequently used to estimate the CO_2 emissions due to operation of automobiles. These fuel consumption equations are regression equations for environmental load emissions obtained by carrying out driving tests in accordance with driving modes set postulating driving on normal national roads in predetermined speed zones. In other words, in a case in which there is special signal control and local congestion is produced, as in this example, driving behavior that is greatly different from the envisaged driving mode occurs, which indicates that it is necessary to carry out estimation by simulation.

The same applies to the LRT, macro data such as electricity consumption cannot include the effects of stops and slopes. Although not investigated in this research, energy efficiency can be increased by introducing hybrid systems to buses and automobiles, in the same way as regenerative braking in the LRT. Estimation by simulation is also effective to verify this effect.

5. Sensitivity Analysis on the Effect of Conversion of Demand from Automobiles to LRT

From the estimate in Section 3, the results obtained indicate that to reduce the CO_2 associated with the LRT development, it is necessary to convert demand from automobiles to LRT. Therefore, a sensitivity analysis was carried out for the change in CO_2 due to automobile operation when there is conversion of demand. Research has been carried out in the past investigating how much conversion is required to enable CO_2 to be reduced by development of the LRT. Therefore, in this research the focus was on the road conditions, to determine how the sensitivity to demand conversion differed in the direction towards the central station where there was congestion and the direction away from the central station where there was no congestion. The CO_2 emissions were estimated for a case in which 10 to 50% of automobiles traveling on the road alongside the LRT converted to the LRT. Here the CO_2 emissions are the total CO_2 emissions originating from automobiles including the surrounding traffic in 1 hour, the same as in Section 4.

Fig. 6 shows the analysis results in the direction towards the central station for the area under consideration. The CO_2 emissions generated by automobiles driving through the area under consideration and the corresponding average traveling speed obtained from the 1 hour simulation are shown. If 20% of the automobile demand is converted to the LRT, it can be seen that the CO_2 emission reduction is greater than the reduction in volume of traffic indicated by the dotted line. The reason for this is considered to be because the effect of congestion at the intersections being cleared and the improvement in the vehicle driving environment is predominant.

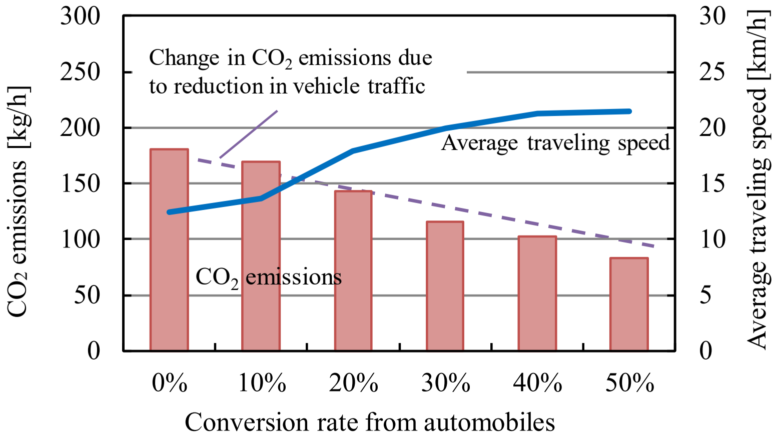

Fig. 6. Sensitivity analysis for conversion of demand from automobiles (towards central station)

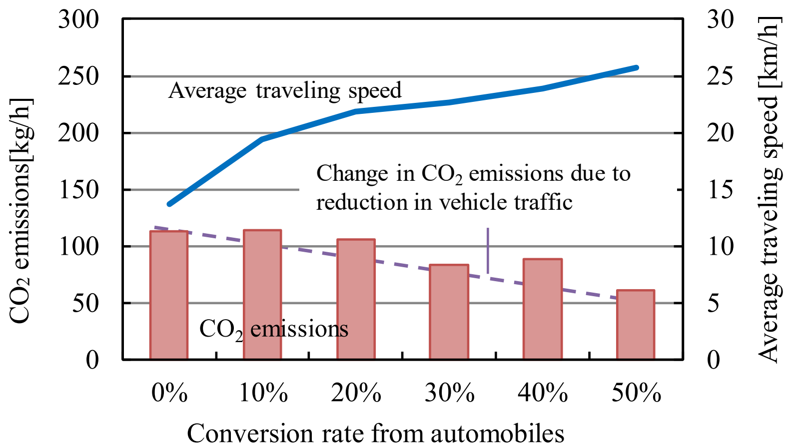

Fig. 7. Sensitivity analysis for conversion of demand from automobiles (away from central station)

On the other hand, in the analysis results for the direction away from the central station in the same area, the extent of the reduction in the CO_2 emissions is small compared with the direction towards the central station (Fig. 7). This is because originally there was no congestion in the direction away from the central station so even though the volume of traffic is reduced by conversion there is no major change in vehicle behavior, and because the volume of traffic on the road under consideration increases due to conversion of traffic from other routes.

It has been shown that the road traffic also greatly affects the sensitivity analysis results for conversion of demand. This section dealt with the amount of conversion of demand, but it is also possible to carry out a sensitivity analysis for the postulated total amount of demand. For example, it is possible to investigate the case that all bus users convert to the LRT or the volume of automobile traffic increases to a level higher than previously.

6. Conclusions

In this research, micro-traffic flow simulation was applied to the evaluation of the life cycle change in environmental load associated with an LRT development project. For estimation in the operation stage, which accounts for a large percentage of the environmental load emissions, it was possible to take into consideration the detailed driving behavior (acceleration, deceleration, stopping, etc.) of automobiles and LRT, which is a major factor in determining the environmental load.

It was possible to take into consideration factors which affect the driving environment such as the state of congestion and signal controls for estimating the changes in CO_2 emissions of fixed route buses, LRT, and automobiles traveling alongside the LRT, using the method constructed in this research. By incorporating micro-traffic flow simulation, it was possible to reflect the changes in detailed driving behavior in the CO_2 estimates. Therefore, it was possible to evaluate in more detail the environmental aspects of measures such as the introduction of public transport priority signals or resolving congestion by improvement of intersections, which change the local driving environment. This methodology can likewise be applied to the evaluation of BRT and other transport mode developments, and such estimating is a task for the future.

References

1) Mikhail Chester, Juan Matute, Paul Bunje, William Eisenstein, Stephanie Pincetl, Zoe Elizabeth and Connery Cepeda, Life Cycle Assessment for Transportation Decision making. Report of UCLA Institute of the Environment and Sustainability.

2) Dan Dong, Huabo Duan, Ruichang Mao, Qingbin Song, Jian Zuo, Jiasong Zhu, Gang Wang, Mingwei Hu, Biqin Dong, Gang Liud, 2018. Towards a low carbon transition of urban public transport in megacities: A case study of Shenzhen, China, Resources, Conservation and Recycling 134, pp.149-155.

3) Andreas Gassner, Jakob Lederer, Georg Kanitschar, Markus Ossberger, Johann Fellner, 2018. Extended ecological footprint for different modes of urban public transport: The case of Vienna, Austria. Land Use Policy 72, pp.85-99.

4) Amar Mohan Shinde, Anil Kumar Dikshit, Rajesh Kumar Singh, Pietro Elia Campana: Life cycle analysis based comprehensive environmental performance evaluation of Mumbai Suburban Railway, India. Journal of Cleaner Production 188, pp.989-1003.

5) Cyrille François, Natacha Gondran, Jean-Pierre Nicolas, David Parsons, 2017. Environmental assessment of urban mobility: Combining life cycle assessment with land-use and transport interaction modelling—Application to Lyon (France). Ecological Indicators 72, pp.597-604.

6) Dohi, M., Sone, S., Takimoto, M., Ogawa, T., Namikawa, Y., 2012. Grounds for the Calculation of Motor Vehicle Emission Factors using Environment Impact Assessment of Road Project etc. (Revision of FY 2010). Technical Note of National Institute for Land and Infrastructure Management 671. [in Japanese]

7) Watanabe, Y., Osada, M. and Kato, H.: Environmental Assessment of Introducing LRT (Light Rail Transit) system -Comparison with Alternative Modes and an Application of Eco-efficiency-, Journal of Life cycle assessment 2(3), pp.246-254, 2006. [in Japanese]