Comparison of Life Cycle Carbon Dioxide Emissions among Urban Passenger Transport Modes

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Abstract

A method of estimating the CO_2 reduction effect of transport modes, such as bicycles and public transport, was constructed using life cycle assessment (LCA). An integrated system consisting on the vehicles and the infrastructure evaluates each transport mode. It calculates CO_2 emission for the case of introduction of transport mode on existing roads. The analysis showed that life cycle CO_2 of bicycles is 80-90% lower than passenger cars per passenger kilometer, and public transport has almost same emission as bicycles as a result of the increase in users. However, the analysis results showed that it is necessary that about 20% change from passenger car use in order to reduce the overall emissions of the road zone.

Keywords: mass transit, bicycle, electric vehicle, environmentally sustainable transport, life cycle assessment

1. Introduction

Bicycles and public transport have less CO_2 emissions per person than passenger cars. However, to introduce these means it is necessary to manufacture vehicles and construct dedicated lanes, and CO_2 emissions are associated with these activities. In addition, it is also necessary to examine whether share the road space by these modes the number of lanes for cars will be reduced, and this makes the fuel consumption of the cars increase by congestion. In order to discuss CO_2 emission properties of bicycles and public transport, these indirect changes in CO_2 emissions due to the introduction of the transport modes should be taken into consideration. The objective of this study was to compare the CO_2 emissions for various urban passenger transport modes using the concept of life cycle assessment (LCA).

2. Evaluation Method and Settings

2.1 Scope of application of LCA

Kato et al.[1] evaluated the introduction of new transport modes by evaluating the system life cycle environmental load (SyLCEL), taking as an integrated transport system the vehicles and the infrastructure, which are evaluated separately in normal LCA. In addition, the environmental load which includes the effect on other traffic modes of providing new dedicated bicycle lanes and dedicated LRT lanes is referred to as extended life cycle environmental load (ELCEL), and there are many examples of the application of this concept.

Based on this, this study estimates extended life cycle CO_2 emissions (ELC-CO_2) of bicycle, electrically assisted bicycle, light rail transit (LRT), and bus rapid transit (BRT). Also, for bicycles, in addition to the CO_2 arising from the vehicles and infrastructure, the CO_2 emissions arising from food resulting from the increased calorie consumption of the people when cycling was estimated as a reference value. It is predicted that the next generation of vehicles such as electrical vehicles (EV) will rapidly be introduced. Therefore a case in which half the gasorin vehicles (GV) changed to EVs, and the reduction in CO_2 resulting from change to bicycle, electrically assisted vehicle, and LRT was evaluated. For all transport modes, previous study indicated the CO_2 emissions associated with maintenance, management, and disposal of vehicles are small. Hence, this study do not consider the estimate. Road repair is regardless of the introduction of the transport modes, so it was not taken into consideration.

Table 1: Basic settings

Period over which traffic occurs [hours]	6-24
Morning rush period [hours]	7-9
Evening rush period [hours]	17-20
1 hour traffic volume in morning rush period / daily traffic volume [%]	10
1 hour traffic volume in evening rush period / daily traffic volume [%]	8.0
Traffic volume in 1 hour apart from rush periods / daily traffic volume [%]	4.3
Life time [years]	60
Electrical power CO_2 emission factor [t-CO_2/kWh][2]	4.49 x 10^4
Number of passenger per car [passengers/car]	1.3

2.2 Basic settings

A 5km road was assumed with three lanes on each side, with reference to an actual example, and a comparison was made of the case where passenger cars only ran on this road and cases where other transport modes could use the road. For bicycles, BRT and LRT a dedicated lane was assumed, each occupying one lane on each side. For taxis and central-area buses there was no reduction in number of lanes, and they shared the lanes with passenger cars.

Table 1 shows the common setting for the introduction of all transport modes. It was assumed that traffic occurs over the time period from 6:00 to 24:00, and that transport demand is concentrated in the morning and evening rush hours. The electrical power CO_2 emission factors was calculated from references[2].

2.3 Evaluation procedure

Fig.1 shows the SyLC-CO_2/ELC-CO_2 estimation procedure as an example of a bicycle. Passenger cars are affected by both reduction in transport volume due to conversion to bicycles, and reduction of car traffic lanes associated with the provision of a new dedicated cycling lane. Travel speed was calculated taking both effects into account by using a relationship between traffic volume and travel speed estimated by a method of previous study[3]. Fuel consumption was calculated by combining this with a regression equation for an explanatory variable for the travel speed indicated by Kudoh et al.[4] However, it was not possible to obtain data on the effect of travel speed on the electrical power consumption of EVs, so this effect was not taken into consideration.

The same method was applied for evaluating the change to public transport modes. LRT and BRT run on a dedicated lane or track, so the change in fuel consumption due to congestion was not taken into consideration.

2.4 Individual settings for each transport mode

2.4.1 Bicycle

Table 2 shows settings of bicycles and electrically assisted bicycles. The dedicated bicycle lane with the pedestrian sidewalk was partitioned using curbstones, and a guard pipe installed in the center of the bicycle lane. Life cycle CO_2 for the installation of a new bicycle lane was calculated from the quantity of raw materials for the curbstones and the guard pipes.

Calorie consumption from riding a bicycle was calculated as the difference from when driving a car (the same value as when commuting by electrical vehicle), using the METS method by the American College of Sports Medicine[5].

Efficiency of electrically assisted bicycles was calculated from battery performance, cruising distance, and tank to wheel efficiency, considering that a part of the calorie consumption is replaced by electrical power.

2.4.2 LRT

Table 3 shows settings for LRT. Using a method from previous study[9], the number of services in each time period was determined from transport demand and congestion rate. Using these values the CO_2 originating from vehicles and their operation was derived. CO_2 originating from infrastracture was estimated by using emission factor about tracks or tram stop[10].

2.4.3 Passenger car

Table 4 shows settings for passenger cars. Although change of demand to bicycles and LRT was produced, it was assumed that there was no change in passenger car ownership and road length, so the CO_2 originating from vehicle and road infrastructure was not estimated. However, when considering conversion to EVs, the CO_2 originating from the vehicle is larger for EVs than for GVs, so the difference was taken into consideration.

2.4.4 BRT

The number of vehicles required were calculated by a method for LRT in previous study[9], based on setting values from Osada et al.[10], and these numbers were used for estimating the CO_2 associated with manufacture and

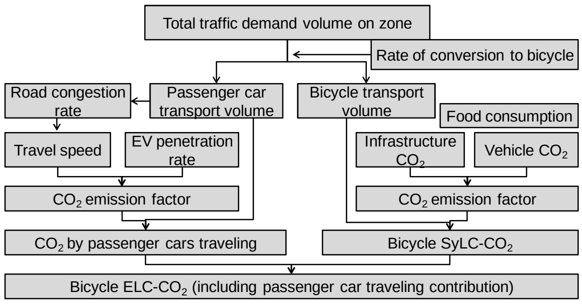

Fig.1: Evaluation procedure (bicycle)

Table 2: Settings for bicycle

Bicycle lane construction CO_2 [t-CO_2/km]	18.1
Bicycle traveling speed [km/hr]	15
Vehicle service life [years]	8
Average distance traveled per day [km/passenger-day][6]	2.93
Bicycle manufacture CO_2 [t-CO_2/bicycle][7]	0.0465
Bicycle calorie consumption (difference from when riding a bicycle) [kcal/hr][5]	337
CO_2 originating from food [t- CO_2/kcal]	0.99
CO_2 from manufacture of electrically assisted bicycle [t-CO_2/vehicle][7]	0.0747
Electrically assisted bicycle cruising range [km][7]	20
Tank to wheel efficiency [%][8]	67
Electrical power assistance percentage [%]	28

Table 3: Settings for LRT

No. of LRT stations [No.]	11
Capacity [persons]	150
Congestion rate during morning rush period [%]	100
Congestion rate during evening rush period [%]	90
Congestion rate during times other than the rush periods [%]	50
Vehicle manufacture CO_2 [t-CO_2/vehicle][1]	70
Vehicle service life [years]	20
Track construction CO_2 [t-CO_2/km][1]	1,510
Tram-stop construction CO_2 [t-CO_2/location][1]	14.9
Infrastructure maintenance CO_2 [t-CO_2/year][1]	4
Unit electrical power consumption when LRT is running [kWh/tram.km][1]	1.5

Table 4: Settings for passenger car

GV manufacture CO_2 [t-CO_2/vehicle][8]	4.2
EV manufacture CO_2 [t-CO_2/vehicle][8]	6.4
Vehicle service life [years]	10
Distance traveled per year [km/vehicle/year]	10,000
Average number of passengers per car [persons/vehicle]	1.3
EV tank to wheel efficiency [%][8]	67

operation of the vehicles.

2.4.5 Taxi and city center bus

The setting values for taxis and buses which were set with reference to existing vehicle types are shown in Table 5. Taxis share the lanes with passenger cars, so it was assumed that the percentage change in fuel consumption from 10-15 mode was the same as for passenger cars. Also, to considerate CO_2 emissions when driving without passengers, the actual driving distance was obtained by multiplying the length of the zone by the inverse of the paid mileage fraction.

Microbuses with a capacity of 29 persons were assumed for the city center buses. The vehicle manufacture CO_2 was assumed to be proportional to the vehicle tare mass, and calculated from the ratio of mass of a passenger car. The number of vehicles operating and the number of vehicles required were calculated using the same method as for BRT.

Table 5: Settings for taxi and bus

Taxi	Vehicle manufacture CO_2 [t-CO_2/vehicle]	4.2
	10.15 mode fuel consumption [km/l]	9.8
	Total distance traveled [10,000km][11]	16
	Average number of passengers [persons/vehicle][11]	1.2
	Paid mileage fraction[11]	0.41
City center bus	Vehicle manufacture CO_2 [t-CO_2/vehicle]	16.6
	CO_2 per unit distance traveled [t-CO_2/vehicle.km]	2.97×10^{-4}
	Capacity [persons/vehicle]	29

3.Calculation Results

3.1 LC-CO_2 of each transport mode

Fig.3 shows the calculation results of LC-CO_2 of the individual transport modes, passenger car and bicycle, taking into consideration vehicle manufacture and energy consumption when operating. Both bicycles and electrically assisted bicycles have values that are an order of magnitude smaller than passenger cars. If calorie consumption by the passenger is not taken into consideration, the electrically assisted bicycle has a value that is about 2.5 times larger than that of a normal bicycle. However, when calorie consumption is taken into consideration, the difference is reduced, and there is a possibility that there would be a reversal of larger/smaller depending on the method generating electricity.

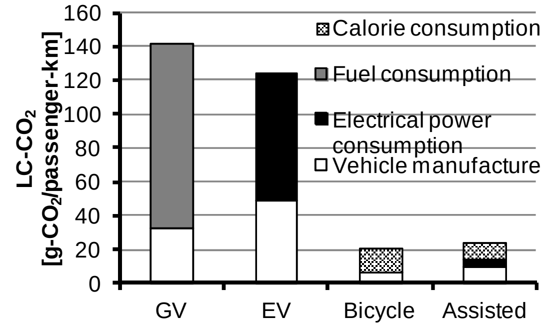

Fig.3: Calculation results for LC-CO_2 for each transport mode (Total traffic demand 10,000 [passengers/day])

3.2 SyLC-CO_2 for each transport mode

Fig.4 shows the calculation results for SyLC-CO_2 for each transport mode. As the volume of transport for LRT and BRT increases, the quantity of emissions originating from infrastructure and vehicles allocated per person per km become smaller, so the SyLC-CO_2 reduces. Conversely, for GV and EV as the volume of transport increases road congestion increases, so the SyLC-CO_2 gradually increases.

As a result, depending on the increase in transport volume, the SyLC-CO_2 for LRT could be smaller than that for the electrically assisted bicycle. However, they are not smaller than the SyLC-CO_2 for the normal bicycle.

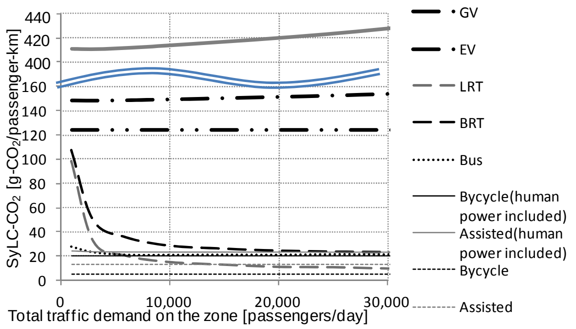

Fig.4: Calculation results for SyLC-CO_2 for each transport mode

3.3 ELC-CO_2 for each transport mode

Figs.5 and 6 show the calculation results for ELC-CO_2 for each transport mode.

Fig.5 shows the change in the ELC-CO_2 when total traffic demand on the zone is 20,000 [persons/day], of which 30% has converted to new transport modes. For the city center bus, passenger car lanes are not reduced, so the effect of CO_2 reduction due to reduction in automobile travel is large, and the ELC-CO_2 is the smallest. When CO_2 emissions originating from human power are not included, the bicycle is superior to LRT and electrically assisted bicycles, but when it is included they are similar. The result for taxis is similar to that for city center buses, the effect of CO_2 emissions as a result of reduction in automobile travel

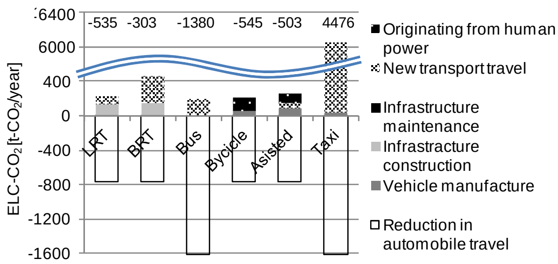

Fig.5: Calculation results for ELC-CO_2 for each transport mode (Total traffic demand 20,000 [passengers/day], conversion rate 30 [%])

is large, but because the paid mileage fraction is low, the actual distance traveled is more than double that of the passenger car, which greatly increases the ELC-CO_2.

Fig.6 show the reduction in ELC-CO_2 when the conversion rate is changed, keeping the total transport demand on the zone at 20,000 [persons/day]. In the traffic modes other than taxi and BRT (LRT, bicycle, bus), the ELC-CO_2 is reduced when the conversion rate is 23% or more when EV spread is not taken into consideration, and 18% or more when it is taken into consideration (Fig.6).

This study, assumed that a dedicated lane would be introduced on one lane on one side of a 5km road having three lanes on each side. However, in cases where the number of lanes, etc., is different, in terms of design it is envisaged that parameters such as traveling speed, would be the same as in this study. Hence, the results would not be greatly different. Also, regarding the total length of the zone, the CO_2 emissions from new transport travel, reduction in automobile travel, facility construction and maintenance, which account for the majority of the ELC-CO_2, are each proportional to the total length of the zone, so ELC-CO_2 is also virtually proportional to the total length of the zone. Therefore the analysis results obtained in this section do not depend on the set total length of the zone.

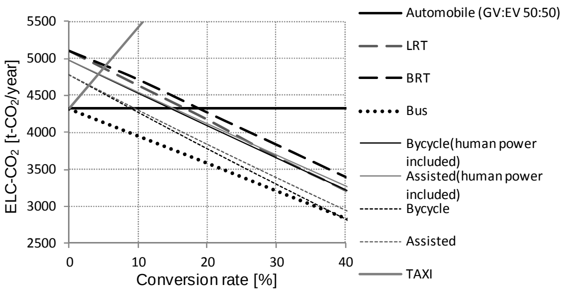

Fig.6: Change in ELC-CO_2 due to conversion rate (penetration of EVs included)
(Total traffic demand 20,000 [passengers/day])

4.Conclusion

In this study, LCA was introduced for the evaluation of the environmental load of the urban passenger transport modes of bicycle, electrically assisted bicycle, LRT, BRT, taxi, and bus. A comparison with the SyLC-CO_2 of passenger cars was carried out, and the potential for reduction in CO_2 due to conversion from passenger cars was investigated using the concept of ELCEL. The results showed that the CO_2 emissions from the manufacture and operation of bicycles were 20% of the emissions from passenger cars, and in terms of SyLC-CO_2 the bicycle was superior to the passenger car, LRT, etc. Also, there was no major difference in the SyLC-CO_2 of bicycles, LRT, BRT, and buses. ELC-CO_2 can consider new installation of a dedicated bicycle lane and LRT tracks, it was also found that if there is not a certain level of conversion from passenger cars, on the contrary CO_2 emissions increase. The actual distance traveled by taxis is more than doubled that of passenger cars, so the SyLC-CO_2 was greater than for passenger cars.

Also, the method of estimating the CO_2 emissions constructed here can be applied to zones other than those envisaged in this study. In order to investigate the effect of reduction in environmental load by the measure of conversion from passenger cars, it is necessary to take into consideration the characteristics of the traffic on the zone under consideration, the spatial structure of the area, the characteristics of the transport modes themselves, and their methods of use.

5. Acknowledgement

This work was supported by JSPS KAKENHI Grant Number 23710055.

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