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ABSTRACT

Towards low carbon society, it is important to figure out carbon dioxide (CO_2) emissions of each transport mode. This study aims to estimate and compare life cycle CO_2 emissions from urban passenger transport with each mode; bicycle, public transport and passenger car. Evaluation boundary includes vehicles, infrastructures of each mode and impacts on existing transport modes such as traffic congestion by decrease of the number of lanes.

Life cycle assessment (LCA) is a systematic approach that provides a rational basis for quantifying the environmental load of each life stage of construction of facilities and production of vehicles; material procurement and transport; construction and operating; renewal. Firstly, system life cycle environmental load (SyLCEL) approach considers the fact that both vehicle production and infrastructure construction stages for the transport systems should be examined since they generate environmental load throughout the whole life cycle. Secondly, the change in life cycle CO_2 emissions by the shift from the passenger cars to the new transport systems are analyzed by the extended life cycle environmental load (ELCEL) approach.

Life cycle CO_2 emissions per passenger-km from bicycles is 80-90% lower than passenger cars. CO_2 emissions from transport systems are not always reduced when cycling roads or LRT, BRT lanes are constructed on parts of existing roads. If few passengers change transport mode from passenger cars to bicycles, LRTs or BRTs, CO_2 emissions would increase. Then, a shift ratio which is necessary to reduce total CO_2 emission is calculated in the following cases; 1) there are no electric cars, 2) electric cars occupy the half of registered cars.

LCA framework is offered for a comprehensive evaluation of environmental impacts in the planning phase of transport systems. It can be concluded that proposed method, considering also the passenger demand level, proved its suitability for environmental performance of passenger transport systems.

Keywords: mass transit, bicycle, electric vehicle, environmentally sustainable transport (EST), life cycle assessment (LCA)

INTRODUCTION

Interest has increased in bicycles and public transport as transport modes that are capable of achieving reductions in CO_2 emissions associated with passenger transport. These modes certainly have small CO_2 emissions per person compared with 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, as a result of sharing the road space with these modes the number of lanes for cars will be reduced, and if this results in congestion the fuel consumption of the cars will increase, so it is possible that this will result in an increase in CO_2 emissions. In order to discuss the low carbon properties of bicycles and public transport, it is necessary that these indirect changes in CO_2 emissions due to the introduction of the transport modes be taken into consideration.

Therefore 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). There have been much studies carried out to date on the application of LCA to public transport modes, in particular by Watanabe and others[1)] and Kato and others[2)] have set the scope of evaluation and established methods of sensitivity analysis. In this study these methods were also applied to transport systems such as bicycles, city center buses, and taxis, for which there are few examples of application of LCA and comparison with other transport modes. As a result of the above, it is possible to comprehensively determine the CO_2 reduction effect for the main urban passenger transport means in accordance with the conditions, such as the amount of demand, etc.

EVALUATION METHOD AND SETTINGS

Scope of application of LCA

LCA is a method of evaluating the environmental load of the product or service being evaluated throughout the overall life cycle from procurement of raw materials, manufacture, use, and disposal. It has been standardized by the ISO, and there are many examples of its application ranging from industrial products, foodstuffs, and transport machinery.

Kato and others[3)] 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 in normal LCA are evaluated separately. In addition, as stated previously, 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, in this study the extended CO_2 emissions (ELC-CO_2) were estimated for bicycle, electrically assisted bicycle, light rail transit (LRT), and bus rapid transit (BRT) transport modes, in addition to the system CO_2 emissions (SyLC-CO_2). 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. On the other hand, gasoline vehicles (GV) were envisaged for passenger cars, but it is predicted that the next generation of vehicles starting with electrical vehicles (EV) will rapidly be introduced. Therefore a case in which half the vehicles changed to EVs, and the reduction in CO_2 resulting from change to bicycle, electrically assisted vehicle, and LRT was evaluated in each case. For all transport modes, from previous study the CO_2 emissions associated with maintenance, management, and disposal of vehicles are small, so they were not included in the estimate. Also, road repair is necessary regardless of the introduction of the transport modes, so it was not taken into consideration.

In this study the focus was on the manufacture of vehicles and infrastructure construction and operation only for comparing functioning units, so they were not affected by external factors such as network shape, etc., and the analysis was carried out within a single zone. Of course, if this method was applied to a study on an actual project, it would be desirable to set the scope to include alternative routes.

Basic settings

A 5km road zone was assumed with three lanes on each side, with reference to an example of investigation for introduction, and a comparison was made of the case where passenger vehicles only ran on this road and cases where other transport modes could use the road so that change from passenger cars was produced. For bicycles and BRT a dedicated lane was assumed, and for LRT dedicated tracks were assumed, each occupying one lane on each side. For taxis and city center 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 hours until 24:00 hours, and that traffic demand was concentrated in the morning and evening rush hours.

It was assumed that the electrical power used by electrically assisted bicycles, LRT, and EVs was the same, and the electrical power CO_2 emission factor (as of 2009, average value for all Japan) was calculated from references [4) and 5)].

Table 1 – Basic settings

Period over which traffic occurs [hours]	6:00-24:00
Morning rush period [hours]	7:00- 9:00
Evening rush period [hours]	17:00-20:00
Morning rush period traffic volume in 1 hour / daily traffic volume [%]	10
Evening rush period traffic volume in 1 hour / 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[4), 5)] [t-CO_2/kWh]	4.49×10^4
Number of persons per passenger car [passengers/car]	1.3

Evaluation procedure

Figure 1 shows the SyLC-CO_2 / ELC-CO_2 estimation procedure using the bicycle as an example. Passenger cars are affected by both reduction in transport volume due to conversion to bicycles, and reduction of traffic lanes associated with the provision of a new dedicated cycling lane. The traveling speed was calculated taking both effects into account by using a relationship between traffic volume for differing numbers of traffic lanes versus traveling speed, which was estimated using a method from previous study[1)]. In addition, the fuel consumption was calculated by combining this with a regression equation for an explanatory variable for the traveling speed indicated by Kudoh and others[6)]. However, it was not possible to obtain data on the effect of traveling speed on the electrical power consumption of EVs, so this effect was not taken into consideration.

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

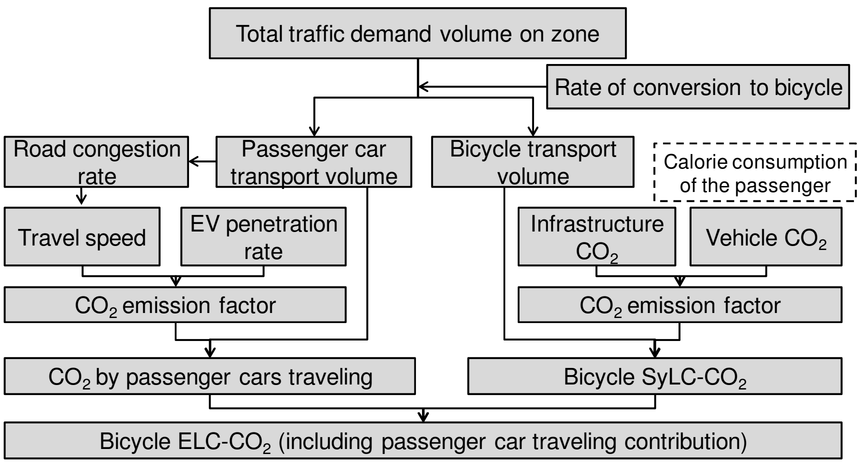

Figure 1 – Evaluation procedure (bicycle)

Individual settings for each transport mode

Settings for bicycles

Table 2 shows the settings for bicycles and electrically assisted bicycles. The boundary of the dedicated bicycle lane with the pedestrian sidewalk was partitioned using curbstones, and a guard pipe installed in the center of the bicycle lane (Figure 2). The life cycle CO_2 (LC-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.

The 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.[7)] Also, the average value of the carbon footprint (CFP) for the group of food products exhibited at "Eco-Products 2008"[8)] was converted into CO_2 using the percentage of GHG emitted in Japan as a whole. By multiplying by this, the CO_2 originating from food resulting from the increase in calorie consumption when riding a bicycle for one hour was derived.

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

As shown in Table 2, the average distance traveled by a bicycle per day is 2.93 [km/passengers/day]. This was calculated from various traveling distances on the envisaged zone, so traveling once on the envisaged 5km zone by bicycle is equivalent to 1.7 persons using a bicycle.

Table 2 – Settings for bicycles

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[9)] [km/passenger/day]	2.93
Bicycle manufacture CO_2[10)] [t-CO_2/bicycle]	0.0465
Bicycle calorie consumption[7)] (difference from when riding a bicycle) [kcal/hr]	337
CO_2 originating from food[8)] [g-CO_2/kcal]	0.99
CO_2 from manufacture of electrically assisted bicycle[10)] [t-CO_2/vehicle]	0.0747
Performance of electrically assisted bicycle Li-ion battery[10)] [V]	25.2
Performance of electrically assisted bicycle Li-ion battery[10)] [Ah]	8.1
Electrically assisted bicycle cruising range[10)] [km]	20
Tank to wheel efficiency[11)] [%]	67
Electrical power assistance percentage [%]	28

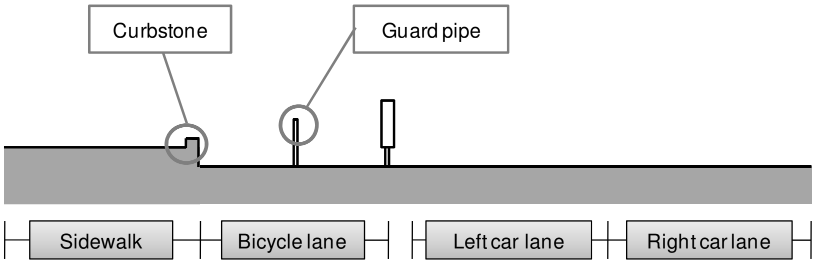

Figure 2 – Cross-section of road on which bicycle lane is introduced

Settings for LRT

Table 3 shows the settings for LRT. Using a method from previous study[2], the number of units traveling in each time period was determined from the volume of demand and the congestion rate. In addition, the number of vehicles required was calculated as the sum of the number of vehicles operating during the morning rush period plus the number of spare vehicles. Using these values the CO_2 originating from the vehicles and their operation was derived. CO_2 emission factors per total kilometer length or per tram stop were calculated in previous study[14].

Table 3 – Settings for LRTs

Number of LRT stations [No.]	11
Capacity [passengers]	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[12] [t-CO_2/vehicle]	70
Vehicle service life [years]	20
Track construction CO_2[12] [t-CO_2/km]	1,510
Tram stop construction CO_2[12] [t-CO_2/location]	14.9
Infrastructure maintenance CO_2[12] [t-CO_2/year]	4
Electrical power consumption rate when LRT is running[12] [kWh/tram-km]	1.5

Settings for passenger cars

Table 4 shows the 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 quantity of road infrastructure, so the CO_2 originating from vehicle and road infrastructure was not estimated. However, when considering the conversion to EVs, the CO_2 originating from the vehicle is larger for EVs than for GVs, so the difference was taken into consideration.

Also, values for the current technical level were used for the tank to wheel efficiency for EVs as indicated in previous study[11].

Table 4 – Settings for passenger cars

GV manufacture CO_2[11] [t-CO_2/vehicle]	4.2
EV manufacture CO_2[11] [t-CO_2/vehicle]	6.4
Vehicle service life [years]	10
Distance traveled per year [km/vehicle/year]	10,000
Average number of passengers per car[13] [passengers/vehicle]	1.3
EV tank to wheel efficiency[11] [%]	67

Settings for BRT

The number of operating vehicles and the number of vehicles required were calculated from a method used for LRT in previous study[2], based on setting values from Kato and others[14], and these numbers were used for estimating the CO_2 associated with manufacture and operation of the vehicles.

Settings for taxis and city center buses

The setting values for taxis and city center 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 take into consideration CO_2 emissions when driving without passengers, the actual distance driven was obtained by multiplying the length of the zone by the inverse of the paid mileage fraction.

Microbuses with a capacity of 29 passengers 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 taxis, city center buses

Taxis	Vehicle manufacture CO_2 [t-CO_2/vehicle]	4.2
	10-15 mode fuel consumption [km/l]	9.8
	Total distance traveled[15] [10,000km]	16
	Average number of passengers[15] [passengers/vehicle]	1.2
	Paid mileage fraction[15]	0.41
City center buses	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 [passengers/vehicle]	29

CALCULATION RESULTS

Calculation results for LC-CO_2 of each transport mode

Figure 3 shows the calculation results for LC-CO_2 for the individual transport means, passenger car and bicycle, taking into consideration vehicle manufacture and energy consumption when operating. For GV the calculation results are shown assuming a total transport demand within the zone of 10,000 [vehicles/day], but the road congestion situation affects the fuel consumption. Also, the CO_2 emissions per passenger-km for public transport modes where passengers ride together depend on the transport demand. The next section describes a sensitivity analysis for the total traffic demand on the zone that takes these into consideration. 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 of generating the electricity.

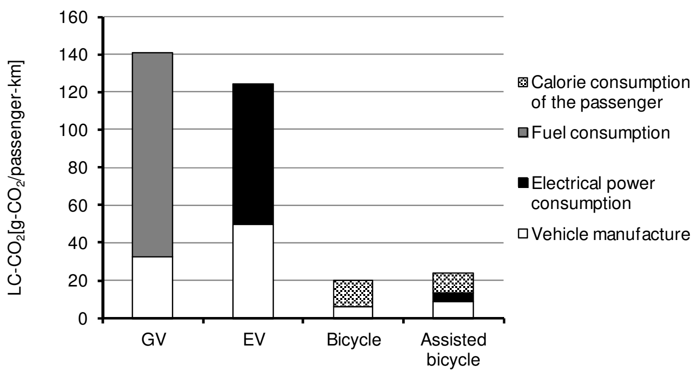

Figure 3 – Calculation results for LC-CO_2 for each transport mode
(Total traffic demand 10,000 [passengers/day])

Calculation results for SyLC-CO_2 for each transport mode

Figure 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 passenger-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 (when "calorie consumption" originating from human power is not included in the calculation).

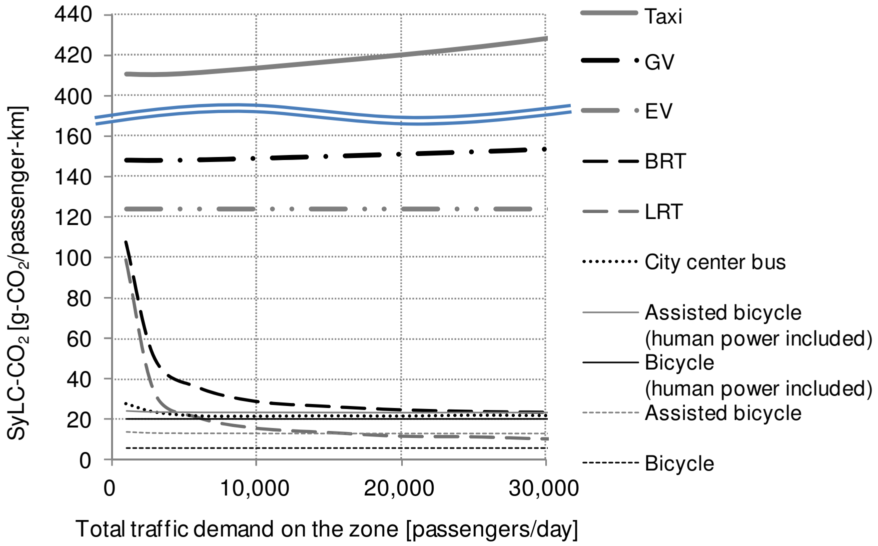

Figure 4 – Calculation results for SyLC-CO_2 for each transport mode

Calculation results for ELC-CO_2 for each transport mode

Figures 5, 6, and 7 show the calculation results for ELC-CO_2 for each transport mode.

Figure 5 shows the change in the ELC-CO_2 when the total traffic demand on the zone is 20,000 [passengers/day], of which 30% has converted to new transport modes. For the city center bus, the 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 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.

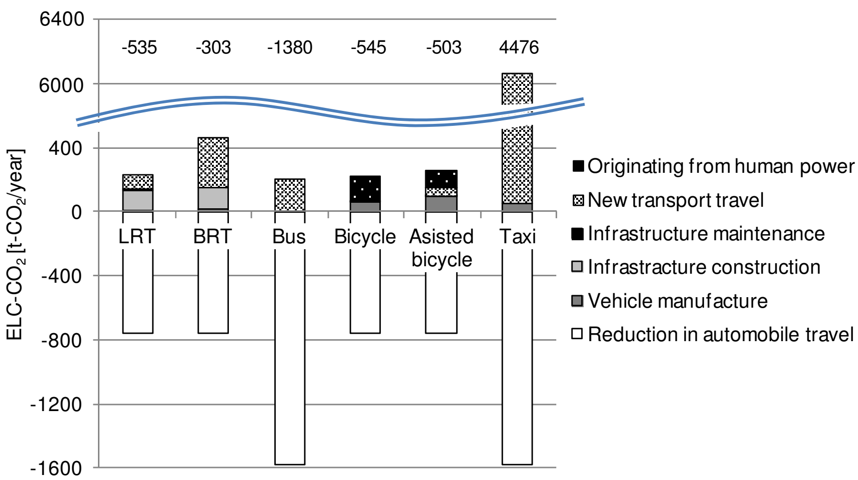

Figure 5 – Calculation results for ELC-CO_2 for each transport mode
(Total traffic demand 20,000 [passengers/day], conversion rate 30 [%])

Figures 6 and 7 show the reduction in ELC-CO_2 when the conversion rate is changed, keeping the total traffic demand on the zone at 20,000 [passengers/day]. In the traffic modes other than taxi and BRT (LRT, bicycle, city center bus), the ELC-CO_2 is reduced when the conversion rate is 23% or more when EV spread is not taken into consideration (Fig. 6), and 18% or more when it is taken into consideration (Fig. 7). This result does not take into consideration the change in fuel consumption of EVs, and similar to GVs, a fair comparison is necessary by taking into consideration the effect of congestion.

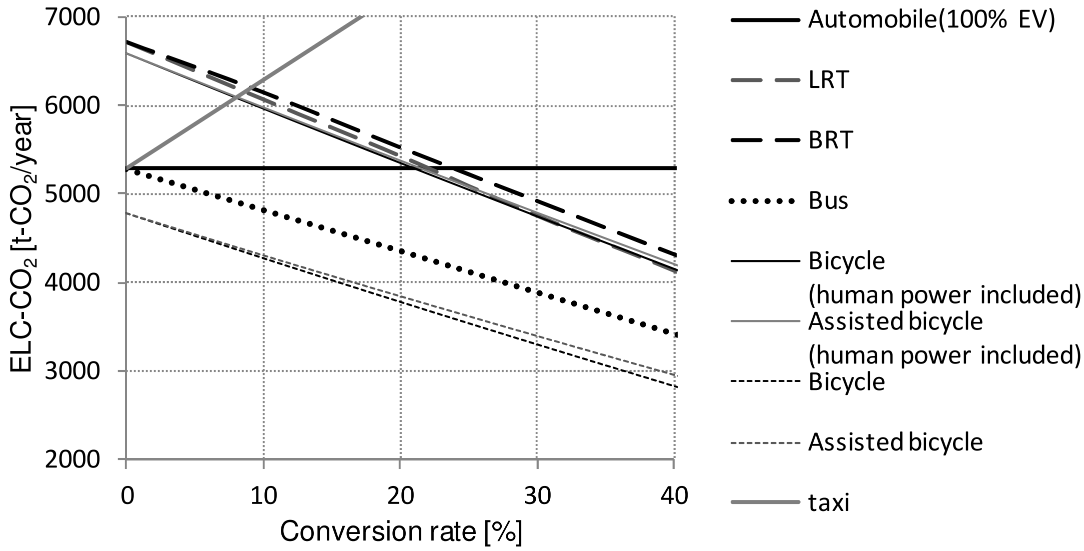

Figure 6 – Change in ELC-CO_2 due to conversion rate (no penetration of EVs)
(Total traffic demand 20,000 [passengers/day])

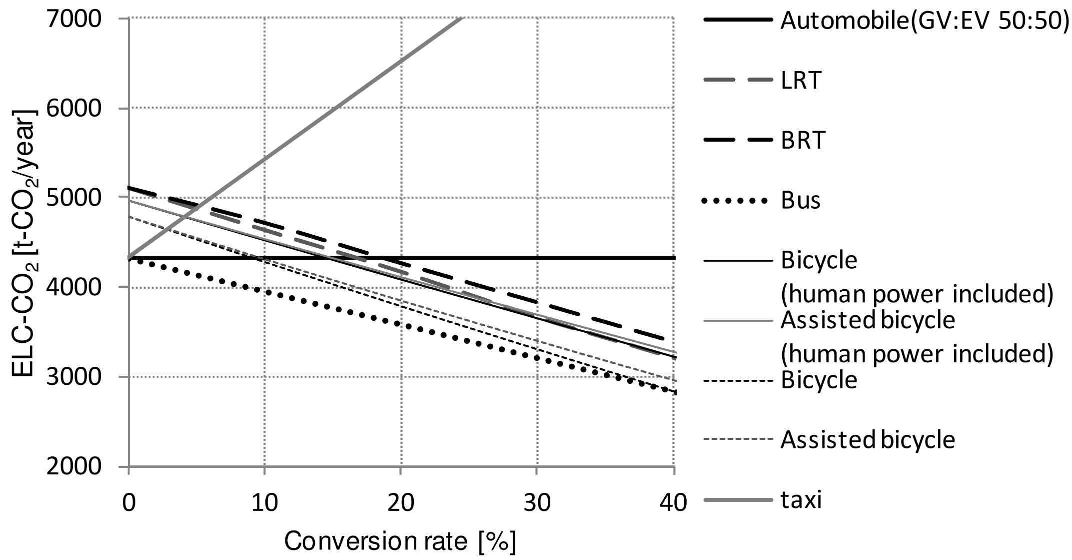

Figure 7 – Change in ELC-CO_2 due to conversion rate (penetration of EVs included)
(Total traffic demand 20,000 [passengers/day])

In this study, it was assumed that a dedicated lane (dedicated tracks) 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, etc., would be the same as in this study, so it is considered that 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.

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 city center 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 originating from the manufacture and operation of bicycles were very small at about 20% 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 city center buses. When ELC-CO_2 is considered, which takes into consideration 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 double 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. In the future we will continue survey research in order to add these factors to the knowledge gained in this study, so that it will be possible to perform a more realistic analysis of the implementation of these measures.

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