Development of Eco-Efficiency Indicators for Passenger Transport Modes Considering Travel Scenes and Situations

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Abstract

This study aims at constructing a methodology for evaluating transport modes in terms of CO_2 emission and performance (e.g., speed, comfort, safety). The proposed indicator is "eco-efficiency"—the ratio of performance life-cycle CO_2 emission. The various performance factors of modes of transport are measured and integrated into a unit of travel speed. Four public transport modes (i.e., railway, subway, light rail transit (LRT), and bus rapid transit (BRT)) and 16 types of private vehicles are analyzed in selected transport scenes and traffic situations. The results indicate that life-cycle CO_2 emission from passenger cars is greater than that from public transport. However, the eco-efficiency of passenger cars exceeds that of public transport taking into account amenities and occupancy in lower volume traffic and leisurely use.

Keywords: eco-efficiency, transportation density, traffic situation, low carbon transport

1. Introduction

Creating a low carbon traffic system within cities is an important issue in Japan. In passenger transport, transport modes in which passengers travel together are usually considered to be low carbon.[1] On the other hand, with the arrival of hybrid cars and electric cars, etc., and with the increase in fuel cost of gasoline cars, the CO_2 emission factors of passenger cars are also decreasing. Under these circumstances, there is a possibility that depending on the conditions such as number of passengers, traffic congestion, situation of use or public transport, etc., the passenger car could be a lower carbon means of transport than public transport in which people travel together.

On the other hand, performance such as being able to quickly and safely arrive at the destination and being able to travel in comfort are also required of transport modes, so it is difficult to pursue "low carbon only." Also, a transport mode with high CO_2 emissions per person can be considered to be an excellent transport mode if it is possible to provide many merits during transport. It is necessary to have a method that is capable of evaluating both the performance of a transport mode and its CO_2 emissions.

In this study, a comparative evaluation of various transport modes was investigated, using eco-efficiency, which is the ratio of performance value and lifecycle CO_2. In this case, the evaluation was made for each travel situations with various transport situations.

2. Definition of Eco-efficiency and Method of Estimation

2.1 Definition of the index

Eco-efficiency in this study is defined as shown in Eq.(1). The lifecycle CO_2 per person in the denominator is calculated taking into consideration the number of vehicles for each transport mode, the degree of congestion, and the difference in distance traveled for each transport mode. The performance of each transport mode in the numerator is obtained by analyzing the constituent factors such as speed and punctuality, and assigning a weighting to each.

$$\text{Eco-efficiency} = \frac{\text{Performance of each transport mode}}{\text{Life cycle } CO_2 \text{ per person}} \quad (1)$$

2.2 Setting transport scenarios and traffic situations

In this study, the purpose, trip length, and number of persons were set as transport scenarios, and the speed of traveling of vehicles, the number of public transport vehicles operated and the rate of congestion, and the difference in distance traveled for each transport mode were set as traffic situations, and the effect of their differences on the performance of the transport mode or the change in CO_2 emissions was estimated.

The vehicle traveling speed, the number of public transport vehicles, and the rate of congestion, which express the traffic situations were calculated using the method of Ito et al.[2]

2.3 Passenger transport modes evaluated

Passenger cars were classified into 16 types that were a combination of vehicle size (minivan, compact car, medium-sized car, and full-sized car), and power category (gasoline vehicle (GV), hybrid vehicle (HV), plug-in hybrid vehicle (PHV), and electric vehicle (EV)). Public transport was considered to be rail (above ground railway, subway), and light rail transit (LRT), and bus rapid transit (BRT) which are expected to be the next generation of public transport.

2.4 Estimation of lifecycle CO_2/passenger-km

2.4.1 Life-cycle CO_2 of passenger cars

The life-cycle CO_2 was used as the evaluation index for environmental load in the denominator of the eco-efficiency. The CO_2 emissions of passenger cars were estimated for each life stage such as vehicle and material manufacture, operation, maintenance, and disposal, using the method of Ito et al.[3] The CO_2 emissions of GV and HV during operation was corrected by determining the average traveling speed using the method of Yamamoto et al.[4] from a relationship between transport density and traveling speed, and correcting the CO_2 emissions in accordance with the average traveling speed using the method of Kudoh et al.[5] The CO_2 emissions of PHV were calculated using the traveling/electrical traveling percentage (utility factor) of HV taking the weighted average of the emissions from vehicles of the same weight category.

2.4.2 Life cycle CO_2 of public transport

The life cycle CO_2 of public transport was estimated as the sum of the CO_2 emitted in the three life stages of infrastructure construction, vehicle manufacture, and vehicle operation. The CO_2 emissions during operation were calculated by multiplying the number of vehicles operating set as a traffic situation by the unit CO_2 emission.

2.5 Performance evaluation of transport modes

2.5.1 Setting performance items

Based on the latent factors for selection of transport mode used in the studies by Morikawa et al.[6] and Muto et al.,[7] the factors that constitute performance were classified, and of these factors 10 items that were envisaged to have a high importance as a result of a preliminary questionnaire survey were selected as the performance items for the transport modes (Table 1). Standards were then set for each performance item and questions for use in a questionnaire were created using the method of Aizaki et al.[8]

2.5.2 Integration of performance items

The performance items were integrated in order to evaluate the performance of transport modes. First, for each public transport mode and for passenger car, i) a weighting was applied to the evaluation of each performance item for each transport scenario, and ii) a standard was set for each performance item for each transport mode for each traffic situation. The performance value was calculated by multiplying the standard and the weighting for each performance item (Eq.(2)).

$$\text{Performance value} = \sum [\text{i}] \times [\text{ii}] \qquad (2)$$

[i] : Weighting of performance item in transport scenario
[ii]: Standard of performance item of transport mode

If the weighting among performance items in the performance value can be determined, the units of each item can also be converted. Travel speed [km/h] is a representative performance value for transport modes, and it is considered to visualize easily, so in this study travel speed is used as the dimension of the performance value.

For passenger cars, the performance value was calculated for medium-sized cars which are the most common type of next-generation passenger car, and the comparison of the four vehicle size types was assumed to be proportional to the car rental price for each size. Also, it was assumed that the performance was not affected by differences in power category.

[i] The weightings for the performance items in the transport scenarios were evaluated using conjoint analysis which is capable of weighting multiple items.

[ii] The standards for the performance items for the transport modes were set based on data such as parameter tables, operation timetables, etc. The traveling speed of passenger cars and the space per person in public transport were varied in accordance with the transport density.

The performance values derived using Eq.(2) are relative values, so for the transport mode for which the lowest performance value was calculated, this value was set to the traveling speed determined from the traffic situation, and the comparison with other modes was performed.

3. Case Study

3.1 Usage scenario and traffic situations set

The transport modes were evaluated for each transport scenario in Table 2. Distance traveled within a city was assumed to be 10 [km]. Distance traveled within regions was assumed to be 50 [km]. In each region the transport density was set to 44,000 [persons/day] and 30,000 [persons/day] based on actual data. Also, the number of persons traveling for each transport scenario was set to four persons for tourism and leisure, and one person for each of the other scenarios.

Table 1: Setting of performance items

Major item	Basic performance	Associated performance	Safety	Cost
Performance item	Speed	Responsiveness	Rate of occurrence of accidents	cost
	Punctuality	Possibility of seating	Rate of occurrence of crimes	
	Space	Access	Privacy	

Table 2: Setting of transport scenarios

	Within cities	Between regions
One person	Commuting to work Traveling to hospital	Commuting to work
More than one person	Shopping Tourism, leisure	Tourism, leisure

3.2 Estimation of lifecycle CO_2 for each transport mode

Fig.1 shows the results of estimation of lifecycle CO_2/passenger-km for each case. The transport mode with the smallest life-cycle CO_2 is LRT in the case of transport of one person within a city, and railway in the case of transport of one person between regions. Also, for transport within a city, the percentage of seating capacity occupied is high in the case of public transport, and for passenger car the traveling speed is low, so the difference between the life-cycle CO_2 for public transport and passenger car is even greater.

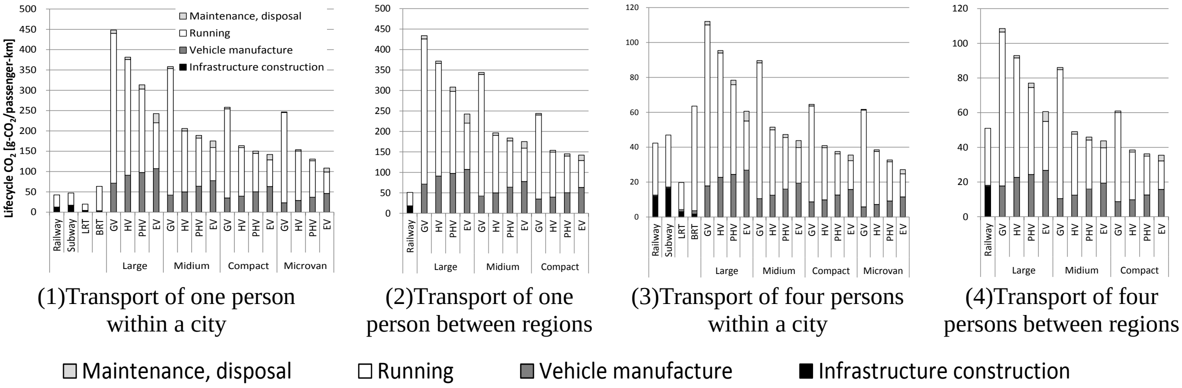
It was found that for transport of four persons, small sized next-generation passenger cars and minivans were lower carbon for transport within a city compared with subway and railway, and for transport within regions medium-sized and small sized next-generation passenger cars were lower carbon compared with railway. This was because the lifecycle CO_2 allocated per one person in a passenger car was reduced by passengers traveling together. Also for transport between regions the transport density is low therefore the percentage occupancy of seats on railways is low, therefore the lifecycle CO_2 per person increases. From the above it can be seen that for transport of four persons within a city or between regions, medium-sized or small sized next-generation passenger cars are lower carbon than rail.

3.3 Performance evaluation of each transport mode

3.3.1 Commuting

Fig.2 shows the performance values other than the transport speed for each transport mode.

For commuting, it can be seen that the performance values for punctuality and responsiveness are large for both transport within a city and transport between regions. This indicates that for commuting, unlike other transport scenarios, priority is given to no delay, and being able to depart at the time to suit one's own convenience. Also, compared with commuting within a city the space per



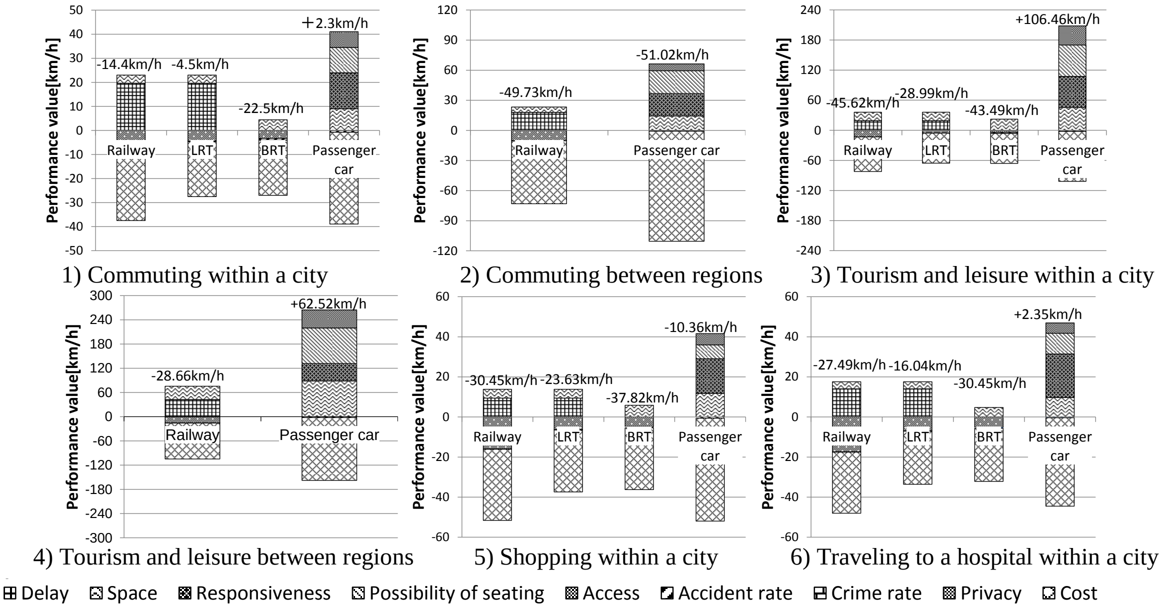
(1)Transport of one person within a city

(2)Transport of one person between regions

(3)Transport of four persons within a city

(4)Transport of four persons between regions

Fig.1: CO_2 emissions in each transport scenario



1) Commuting within a city

2) Commuting between regions

3) Tourism and leisure within a city

4) Tourism and leisure between regions

5) Shopping within a city

6) Traveling to a hospital within a city

Fig.2: Results of performance evaluation of transport modes in each transport scenario

person, the privacy, and the cost are large for commuting between regions. The reason for this is considered to be because in actual public transport within a city, during the commuting time periods the space per person is small, and privacy is low, therefore these factors tend to be ignored. Also, the reason why the importance of cost is large is considered to be because for commuting between regions virtually every day, the cost is large compared with the other transport scenarios.

3.3.2 Tourism and leisure

For tourism and leisure, the importance of space and privacy is large for both transport within a city and transport between regions. For tourism and leisure comfortable transport is more important than time, so the performance value of passenger cars with large space and privacy is evaluated highly. Conversely, for public transport with excellent punctuality but small space, the performance value is low.

3.3.3 Shopping

For shopping within a city, it can be seen that the performance value per unit cost is large, the same as for commuting between regions. Money is spent after traveling, so it is considered that the awareness of minimizing cost when traveling is comparatively emphasized.

3.3.4 Traveling to a hospital

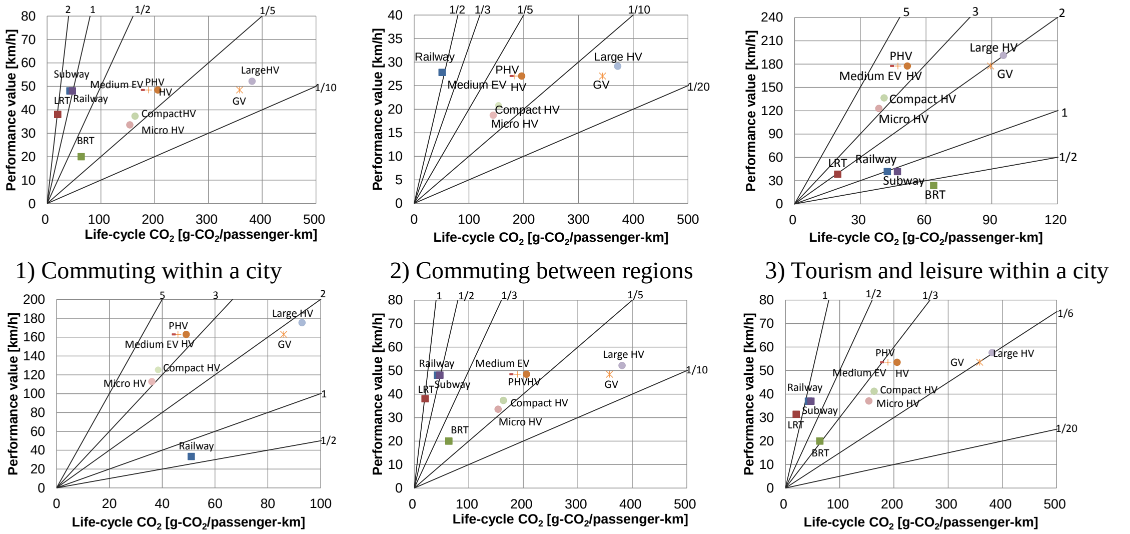
For traveling to a hospital, it can be seen that the performance value of time responsiveness is large compared with the other transport scenarios. It is considered that emphasis is placed on being able to immediately board a vehicle because one's bodily condition is not good.

3.4 Evaluation of eco-efficiency for each transport mode

3.4.1 Commuting

Fig.3 shows the relationship between the performance values of the transport modes and the life-cycle CO_2 for each transport scenario.

For both transport within cities and between regions, public transport is superior to the passenger car in both life-cycle CO_2 and performance value, and the eco-efficiency of public transport is about five times or more than that of the passenger car.



1) Commuting within a city
2) Commuting between regions
3) Tourism and leisure within a city
4) Tourism and leisure between regions
5) Shopping within a city
6) One person traveling to hospital within a city

Fig.3: Eco-efficiency of transport modes in each transport scenario

3.4.2 Tourism and leisure

For tourism and leisure, the eco-efficiency of the passenger car is 2-8 times that of public transport. This is because transport of four persons was assumed, therefore the life-cycle CO_2 per person for the passenger car was similar to that for public transport, and for tourism and leisure the emphasis is placed on comfort. Therefore, the eco-efficiency of the passenger car was higher than the low carbon transport modes such as LRT and BRT.

3.4.3 Shopping, traveling to a hospital

For shopping, it was found that the eco-efficiency of public transport is 3-10 times that of the passenger car. The performance value of the passenger car is higher than that of public transport, but for transport within cities the life-cycle CO_2 of the passenger car is very high compared with that of public transport. Therefore the eco-efficiency of public transport is higher.

On the other hand, for transport to a hospital, the life-cycle CO_2 for each transport mode was the same as for shopping, but the performance value for the passenger car is higher compared with public transport, therefore the difference in eco-efficiency between public transport and the passenger car is reduced.

4. Conclusions

In this study, a comparative evaluation of passenger transport modes for various transport scenarios was carried out using an eco-efficiency index which can take into consideration many types of performance elements. The results and knowledge obtained are as follows.

1) As a result of estimating the life-cycle CO_2 for each transport scenario and traffic situation, it was found that when the number of travelers is large and the transport density is small which are low carbon compared with above ground rail.
2) It was found that for transport scenarios where the emphasis is on items relating to time, such as transport time and punctuality, etc., public transport is superior, and for transport scenarios where the emphasis is on items relating to comfort, such as space per person and privacy, etc., the passenger car is superior.
3) Even transport modes with a large life-cycle CO_2 can have a high eco-efficiency if the performance value in a transport scenario is high, and can have an eco-efficiency that is similar to that of transport modes with small life-cycle CO_2.

5. Acknowledgement

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