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LIFE CYCLE CO_2 EMISSIONS OF VARIOUS PASSENGER TRANSPORT MODES AT DIFFERENT PASSENGER OCCUPANCIES

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The CO_2 emissions per passenger-km from passenger transport depend on the number of passengers carried, or vehicle occupancy. While most existing studies estimate CO_2 emissions generated during operation stage only, this study introduces a life cycle assessment (LCA) approach and considers CO_2 emissions generated during infrastructure construction and the production of vehicles. Through this study, the effect of higher occupancy and technological advancement on CO_2 reduction is revealed. It is found that the provision of mass transit can contribute to a reduction in CO_2 emissions given the present level of emissions by passenger cars. However, a small-capacity mass transit system with large infrastructure will lose its superiority in CO_2 emissions as innovation takes place in automobile technology and automobile use is improved.

Key Words : *CO_2 emissions, low carbon transport, life cycle assessment, mass transit*

1. INTRODUCTION

In Japan, transport sector accounts for nearly 20% of all human CO_2 emissions. Passenger cars are responsible for nearly 50% of these emissions within the transport sector. Although CO_2 emissions from passenger transport have been gradually declining since the sharp increases experienced in the 1990s, it is believed that much greater reductions are necessary.

One measure to reduce CO_2 emissions from passenger transport is to promote the use of mass transit modes, such as railways and buses, which produce less CO_2 per passenger. Accordingly, many public transport authorities nationwide are either in the process of or are planning to implement more environmentally minded systems with lower CO_2 emissions. In addition, Japan's institutional commitment to reduce emissions via public transit policy is indicated by endorsements of environmentally sustainable transport (EST) by the Ministry of Land, Infrastructure, Transportation and Tourism, the Ministry of the Environment, and the National Police Agency as well as the Ministry of Environment's recommendations [1] for achieving a low carbon society in March, 2010 publication entitled "A Mid-Term Road Map for Preventing Global Warming".

The CO_2 emissions factor (measured in passenger-km or ton-km) decreases as the number of passengers or amount of freight carried by a vehicle increases. According to the 2008 Transportation Annual Statistical Report[2], the national average for passengers per private vehicle per trip was 1.47. Mass transit, while having higher emissions than passenger cars, can transport hundreds of passengers who would have occupied dozens of passenger cars otherwise. Therefore, on a per person unit, emissions from mass transit are less than emissions from passenger cars.

However, the common recongnition that public transport systems are good for the environment does not apply to mass transit routes where the small number of passengers means that CO_2 emissions per passenger-km do not fall below those of passenger cars. Further, where new mass transit routes are to be constructed, CO_2 emissions resulting not only from operation but also from infrastructure development and vehicle production need to be evaluated.

If public transport authorities do not take these facts into account when implementing their plans to reduce CO_2 emissions, they run the risk of actually increasing emissions. It is important for mass transit systems to address the issue CO_2 emissions today so that they do not become the dominant emitter in the future. Thus, when comparing passenger-km CO_2 emissions between mass transit and passenger cars, it is important to note that different assumptions can produce different results.

This study proposes an index for evaluating CO_2 emissions from mass transit systems: the passenger occupancy per vehicle at which the CO_2 emissions per passenger-km are equal to those of passenger cars. In addition, the impact of changing the number of passenger car occupants as well as fleet improvements on emissions is analyzed.

2. AN OVERVIEW OF PASSENGER-KM CO_2 EMISSIONS ESTIMATION

Calculating the CO_2 emissions for various forms of transport generally focuses on the amount of energy consumed as well as its source. In particular, there have been numerous evaluations of the various vehicular technologies and their subsequent fuel and/or electricity consumption. With regard to passenger cars, the Ministry of Land, Infrastructure, Transportation and Tourism[3] publishes annually the fuel economy for each model produced (10-15 mode as well as JC 08 Mode). With the commercialization of hybrid technology, passenger vehicles have seen significant increases in fuel economy. Railways also have implemented new technology that reduces electricity consumption.

For example, Ogasa [4] measures the efficiency of storage and energy use of rail vehicles equipped with lithium ion batteries and calculates the train's environmental impact. In other investigations [5],[6], the energy consumption and environmental load from rail vehicles with double layer capacitors or fuel cells are measured. In addition, there are some studies that calculate the CO_2 emissions from diesel trains on non-electrified lines and hybrid trains [7],[8].

Although it is possible to compare CO_2 emissions using these results, they do not include estimates of emissions resulting from updating infrastructure or implementing new technology. Thus, the purpose of this research is not to calculate individual vehicular emissions, but the emissions of the system as a whole. In order to calculate the environmental impact of the entire system, the life cycle assessment (LCA) method is applied [9]. This method takes into account not only CO_2 resulting from operation of the system, but also that resulting from construction and maintenance over the system's lifetime. In order to estimate emissions using the LCA method, assumptions concerning number of passengers, frequency of trips, and speed are necessary. Previous research employing this method often refers to these values as "constants."

In reality, however, these values are constantly changing. With this in mind, Takata et al. [10] have developed an index that calculates environmental impact based on distance moved per unit weight and is not affected by the number of passengers. Using this method, the analysis cannot be based upon traffic volume.

In contrast, a number of previous studies base emissions estimates on the number of passengers per vehicle. Ohno et al. [11], for example, focusing on diesel locomotives, developed a method for calculating the fuel consumption per passenger, calling this parameter the locomotive's "Energy Saving Index". This, however, does not account for future emissions, as it requires knowledge of the amount of fuel actually consumed. Therefore, in this study we will estimate the total CO_2 emissions from railways, monorails, light rail transit (LRT) and buses resulting from infrastructure provision and vehicle production as well as operation using the life cycle assessment (LCA) method. The resulting assessment method is applicable not only to the evaluation of existing railway lines but also to cases where new lines are planned or existing lines are updated through electrification or other improvements.

With the introduction of hybrid and electric vehicles in recent years, comparisons of this sort are important when evaluating the effectiveness of this "eco-friendly" technology in reducing CO_2 emissions. Also, because some rail lines operate both electrified and diesel trains, we estimate emissions separately for the two technologies.

3. METHOD OF ESTIMATING CO_2 EMISSIONS

(1) Mass transit systems considered in this study

The types of mass transit considered in this study are railways, automated guideway transit (AGT), monorails, high-speed surface transport (HSST) by normal conducting MAGLEV system, light rail transit (LRT), guide-way buses (GWB), and bus rapid transit (BRT). Railways are classified into electrified and non-electrified (diesel powered) sections for the purpose of calculation.

With respect to private passenger cars, in order to study the effect on CO_2 reduction of innovations offered by new technologies, hybrid and electric cars on sale as of 2010 as well as conventional gasoline-powered cars are included.

(2) Scope of mass transit system evaluation

Table 1: Passenger vehicle capacity, scheduled speed, and CO_2 emissions factor of mass transit systems

Type of mass transit system	Vehicle capacity [passenger /vehicle]	Number of passenger vehicles per train [vehicle/train]	Scheduled speed [km/h]	CO_2 emissions factor		
				Operation [g-CO_2/car-km]	Construction and maintenance of track [t-CO_2/km /60 years]	Production of vehicles [t-CO_2 /vehicle]
BRT	74	1	20	1,120	1,870	15.5
GWB	74	1	30	865	21,600	15.5
AGT	50	4	30	555	21,600	26.2
HSST	80	3	30	2,253	20,500	75.7
Monorail	95	4	30	982	17,800	59.3
LRT	150	1	20	833	4,100	76.5
Electric railway	130	4	40	1,390	23,300	70.6
Non-electric railway (Diesel)	130	2	40	1,750	23,300	70.6

The CO_2 emissions of mass transit systems are calculated from the life-cycle energy consumed during construction and maintenance of track, production of passenger vehicles, and system operation, a figure known as system life cycle CO_2 (SyLC-CO_2)[12].

Tsujimura et al.[13] revealed that the CO_2 emissions resulting from the disposal of mass transit passenger vehicles accounts for only a small proportion of life cycle emissions. Accordingly, CO_2 emissions relating to the disposal phase are not taken into account in this evaluation.

For passenger cars, the CO_2 emissions resulting from construction and maintenance of roads are not included in the evaluation. This means that the evaluation is based on the scenario that a new mass transit system is constructed to run in parallel to roads that have already been constructed. Moriguchi et al.[14] indicated that the CO_2 emissions from the construction and maintenance of roads allotted to one passenger car account for about 10% of the life cycle CO_2 emissions. Accordingly, a more comparative evaluation can be obtained by adding this percentage to the results shown in Chapter 3 for passenger cars.

(3) Method of calculating SyLC-CO_2

a) Construction and maintenance of track

The CO_2 emissions resulting from construction and maintenance of mass transit routes are calculated by multiplying the quantity of materials input[15] in each phase by the CO_2 emissions per unit length of a route[16] and the route length. Here, route length is assumed to be 10 km.

b) Production of vehicles

The CO_2 emissions resulting from passenger vehicle production are calculated by multiplying the quantities of materials and energy consumed during fabrication by the appropriate CO_2 emissions factor[16]. In calculating the CO_2 emissions resulting from the production of electric railway vehicles, the actual material composition of a stainless steel car and the energy consumed during production[15] are used. For the case of diesel railway vehicles, the electric vehicle values are corrected in proportion to the vehicle weight. For buses, the CO_2 emissions resulting from production are calculated from passenger car values in proportion to the vehicle weight. Mass transit passenger vehicles and buses are assumed to be replaced every 20 years and every 15 years, respectively. The number of mass transit passenger vehicles, n, required to provide service on a line can be calculated from Equation (1).

$$n = \frac{N \times l}{V \times T} \times S \qquad (1)$$

Where, N = number of operations per day, l = track length, V = scheduled speed, T = operating hours per day, and S = number of passenger vehicles per coupled unit.

c) Operation

The CO_2 emissions resulting from operation of a mass transit system are calculated by multiplying the power/fuel consumption per distance traveled by the CO_2 emissions factor[17]. The power/fuel consumption per distance traveled for each mass transit system was obtained for use in the calculation from data made available by transit operators[15].

For the CO_2 emissions factor of gasoline-powered passenger cars, the domestic average calculated by Matsuhashi et al.[18] in 1999 is used. For hybrid passenger cars, the 10-15 mode value of fuel consumption of the cars[3] is converted into actual fuel consumption using an estimation equation[19]. For electric-powered passenger cars, the published travel distance per charge of the cars in question is divided by the power consumption[20] and multiplied by the CO_2 emissions factor[17].

The CO_2 emissions factors of the mass transit systems in each phase are listed in Table 1, along with the set values of vehicle capacity, number of passenger vehicles per coupled unit, and scheduled speed. Various conditions required for the calculation of the SyLC-CO_2 are listed in Table 2. In the analysis that follows, it is assumed that all transit systems have the same number of operations per day and the same daily operating hours. It would also be possible to perform a sensitivity analysis using different values of these variables and analysis in which the values are replaced with those of actual systems.

4. ESTIMATED CO_2 EMISSIONS OF MASS TRANSIT SYSTEMS

(1) SyLC-CO_2 of mass transit systems per passenger-km

If measures to promote the use of mass transit modes persuade only few passengers change mode from passenger car to mass transit, they will not reduce CO_2 emissions resulting from passenger transport. Further, if the CO_2 emission factor of passenger cars falls below that of mass transit, CO_2 emissions will be increased by shifting passengers from passenger car to mass transit modes.

Fig. 1 shows the estimated SyLC-CO_2 of mass transit systems per passenger-km when operating at full capacity (100% passenger load factor; volume carried = capacity), along with the passenger volume. Because the capacity of passenger vehicles differs among mass transit systems, SyLC-CO_2 per passenger-km varies. For example, the CO_2 emissions factor of GWB and AGT resulting from the construction and maintenance of tracks are assumed to be the equivalent, but there is a factor of about 2.7 in CO_2 emissions per passenger-km. The CO_2 emissions of mass transit systems resulting from track construction account for a large proportion of the SyLC-CO_2: 50% or more except in the case of BRT.

Fig. 2 shows the estimated SyLC-CO_2 of mass transit systems per passenger-km when the transport density is assumed to be constant. The selected density is 10,000 [passengers/day]. The SyLC-CO_2 of the systems per passenger-km at this constant density is higher than the SyLC-CO_2 at full capacity because the systems are operating at less than full capacity. The SyLC-CO_2 of railway, monorail, HSST, and AGT systems per passenger-km at full capacity is relatively high. This is because such systems operate on the basis of trains of several vehicles so total capacity is quite large; as noted above, SyLC-CO_2 per passenger-km varies greatly with the number of passengers per train.

Table 2: Set values for calculating SyLC-CO_2 of mass transit systems

Lifetime [year]	60
Track length [km]	10
Renewal period of passenger vehicles (others than buses) [year]	20
Renewal period of buses [year]	15
Number of operations [/day]	250
Operating hours [hr/day]	18

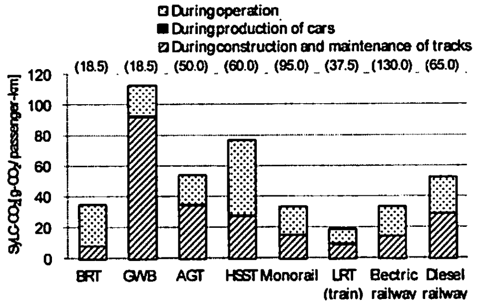

Fig. 1: SyLC-CO_2 of mass transit systems per passenger-km (at full capacity; parentheses indicate the passenger volume [10,000 passenger-km/day])

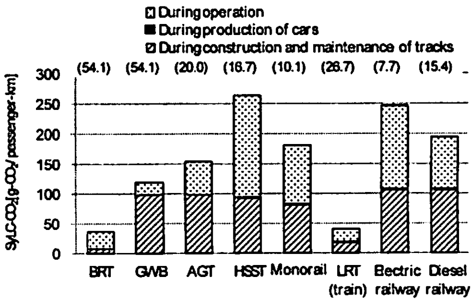

Fig. 2: SyLC-CO_2 of mass transit systems per passenger-km (transport density: 10,000 [passengers/day]; parentheses indicate passenger load factor [%])

(2) Comparison of SyLC-CO_2 between passenger cars and mass transit systems

Fig. 3 shows the relationship between the number of passengers per vehicle and the SyLC-CO_2 of mass transit systems and passenger cars, calculated using the values given in Table 1. Curve A in the figure represents gasoline-powered passenger cars. Here, the SyLC-CO_2 of a gasoline-powered passenger car carrying 1.4 passengers is taken to be 209 [g-CO_2/passenger-km]. This is a constant value, or domestic average, and it would be possible to include such variations by setting variables for road

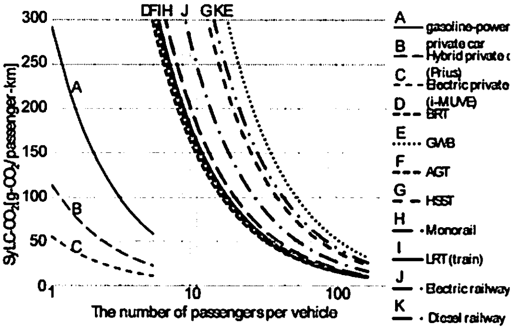

Fig. 3: Relationship between passenger occupancy per vehicle and the SyLC-CO_2 of mass transit systems and passenger cars

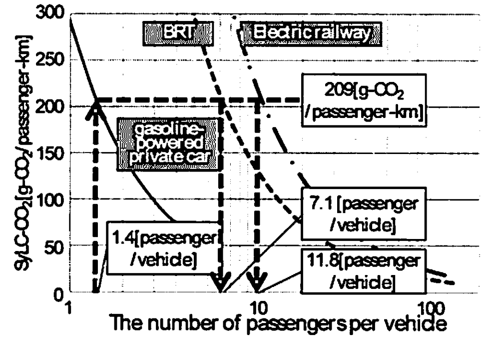

Fig. 4: Relationship between passenger occupancy per vehicle and the SyLC-CO_2 of passenger cars, BRT, and electric railway

Table 3: Mass transit system vehicle occupancy at which the CO_2 emissions per passenger-km are equal to those of passenger cars [passenger/car] (passenger load factor [%])

Type of passenger car compared	Gasoline-powered		Gasoline-powered		Hybrid	Electric
Occupancy of passenger car	1.4		2	4	1.4	
Range of evaluation	CO_2 emissions during operation only	SyLC-CO_2	SyLC-CO_2		SyLC-CO_2	
BRT	5.4 (7.3)	7.1 (9.5)	10.1 (13.6)	20.2 (27.3)	18.1 (24.4)	37.2 (50.2)
GWB	4.1 (5.6)	23.1 (31.2)	33.0 (44.5)	65.9 (89.1)	59.1 (79.9)	121.4 (164.0)
AGT	2.7 (5.3)	7.4 (14.9)	10.6 (21.2)	21.2 (42.4)	19.0 (38.1)	39.1 (78.2)
HSST	10.8 (13.5)	16.9 (21.2)	24.2 (30.2)	48.4 (60.5)	43.4 (54.2)	89.1 (111.3)
Monorail	4.7 (5.0)	8.7 (9.2)	12.5 (13.1)	24.9 (26.2)	22.3 (23.5)	45.9 (48.3)
LRT	4.0 (2.7)	7.8 (5.2)	11.1 (7.4)	22.2 (14.8)	19.9 (13.3)	40.9 (27.2)
Electric railway	6.7 (5.1)	11.8 (9.1)	16.9 (13.0)	33.8 (26.0)	30.3 (23.3)	62.3 (47.9)
Diesel railway	8.4 (6.4)	18.7 (14.4)	26.7 (20.5)	53.3 (41.0)	47.8 (36.8)	98.2 (75.5)

conditions.

Fig. 4 shows the SyLC-CO_2 of passenger cars, BRT, and electric railway extracted from Fig. 3. The passenger occupancy per vehicle in the BRT and electric railway systems at which the CO_2 emissions per passenger-km are equal to those of passenger cars is 7.1 for BRT and 11.8 for electric railway. If usage of BRT and railway is below these values, they are inferior to passenger cars with respect to emissions. It is clear from this that CO_2 emissions from the various systems can be easily compared using passenger occupancy per vehicle as an index.

BRT produces same CO_2 emissions per passenger-km as electric railway with fewer passengers. In terms of passenger load factor, defined as the ratio of actual passengers per vehicle to the vehicle's capacity, the equivalence point is 9.1% for electric railway and 9.5% for BRT, both of which are achievable values. It should be noted, however, that passenger load factor is different in the case of a railway, because passenger vehicles can be loaded beyond a factor of 100%. This means that railway passenger vehicles have greater marginal capacity than those of BRT even at the same passenger load factor.

The first two columns of Table 3 list the number of passengers per vehicle and the passenger load factor for the mass transit systems at the point where CO_2 emissions per passenger-km are equal to those of passenger cars (again, when carrying 1.4 passengers each). Looking at operational CO_2 emissions only, the AGT, LRT, and GWB appear advantageous. However, when the SyLC-CO_2 figures are compared, the advantage of GWB decreases significantly because the required infrastructure is large and track construction consumes large quantities of materials. The high vehicle occupancy of HSST when the systems are compared based on operational CO_2 emissions only results from the considerable energy required to magnetically levitate the passenger vehicles. Comparing electric trains with diesel trains, the former produce less CO_2 emissions than the latter. Generally the number of users of non-electrified sections of railway, where diesel is used, is low. As a result, there may be cases where such sections could be replaced with BRT, since it does not require major new infrastructure.

(3) Changes in SyLC-CO_2 as passenger car occupancy increases

One measure sometimes used to reduce CO_2 emissions per passenger-km of passenger cars is carpooling. To investigate the effects of this, results for mass transit occupancy and load factor at which SyLC-CO_2 per passenger-km becomes equal to that of passenger cars carrying 2 and 4 occupants are also listed in Table 3. The SyLC-CO_2 per passenger-km of passenger cars at these levels of occupancy is 0.7 and 0.35 of the value when occupancy is 1.4, respectively. Consequently, the point of equality in SyLC-CO_2 per passenger-km between passenger cars and mass transit systems increases by a factor of 1.4 and 2.8, respectively. Then the passenger load factor for GWB at the point of equality with passenger cars is high, at 89.1%. This figure would be difficult to achieve. Conversely, it is clear that passenger carpooling has an effect on CO_2 reduction equivalent to a shift to public mass transit systems.

(4) Effect of low CO_2 emission passenger cars

Table 3 also includes figures for transit occupancy per passenger vehicle at the point where CO_2 emissions per passenger-km are equal to those of hybrid and electric passenger cars (columns five and six; based on car models currently on sale). These passenger cars emit less CO_2 in operation than gasoline-powered cars, so the number of passengers that must be carried by a mass transit system to reach equality increases significantly. The factor is 2.6 and 5.3, respectively, for hybrid and electric cars. This indicates that the advantage of mass transit systems relatively falls if they do not take advantage of measures to reduce CO_2 emissions, including technological advances. To reduce the CO_2 emissions per passenger-km of existing GWB and HSST systems to a level comparable to that of electric passenger cars, the passenger load factor would have to exceed 100%. The operation of GWB and HSST systems under these conditions would be very difficult.

5. CONCLUSION

This study compares the CO_2 emissions per passenger-km of passenger cars and mass transit systems applying the LCA approach. The passenger occupancy of various mass transit systems at which the CO_2 emissions per passenger-km are equal to those of passenger cars is calculated. This is used as an index for comparing CO_2 emissions from the various systems. The results illustrate the effects of a shift from passenger cars to mass transit systems on CO_2 reduction, taking into account the need to construct infrastructure for mass transit. Also, occupancy and technological innovation in passenger car are considered.

These results demonstrate that: (1) under current conditions of passenger car usage, CO_2 emissions can be reduced by the construction of new mass transit systems and (2) mass transit systems that require considerable infrastructure and have small passenger vehicle capacity will have little effect on reducing CO_2 if carpooling is taken up and technological innovation continues in passenger car design. The study assumes that mass transit systems operate at constant timing and that the passenger volume remains constant throughout the day.

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