Evaluating Life Cycle Carbon Dioxide Emission from Alternative Inter-regional High Speed Passenger Transport Systems

Naoki SHIBAHARA, Hirokazu KATO, Yoshitsugu HAYASHI
Nagoya University
C1-2(651) Furo-cho, Chikusa-ku, Nagoya, Aichi
nshiba@urban.env.nagoya-u.ac.jp

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ABSTRACT
The importance of reducing carbon dioxide (CO$_2$) emission from transport activities from long-distance and high-demand sections is recognized especially in developed countries. This study aims to compare CO$_2$ emission from Shinkansen high speed railway with emissions from air transport by employing LCA method. Here it is assumed that only existing airports are used for air transport but Shinkansen is a newly provided infrastructure considering the construction of this system in the analysis. Life cycle CO$_2$ is calculated for each case. Further, an eco-efficiency indicator including travel speed as a service level factor is defined and calculated. In a case of fixed distance, life cycle CO$_2$ (eco-efficiency) from air transport does not vary with the number of passengers. On the other hand, life cycle CO$_2$ from Shinkansen is inversely proportional to the number of passengers. A sensitivity analysis with passenger volume can be used to find a break even point where life cycle CO$_2$ from Shinkansen and from air transport is equal. The conditions for reducing life cycle CO$_2$ emission by proving Shinkansen as an alternative system to air transport depend on the number of passenger and the volume of infrastructure construction for Shinkansen.

INTRODUCTION
As of 2006, the ratio of greenhouse gases emitted by the passenger transport sector in Japan was 12.0%, and air transport accounts for only 6.2% of the total transport sector (0.8% of the total emission), and is comparatively low. However, there is the general idea that the air transport will be the slowest sector in shifting away from carbon fuels. Therefore air transport contribution is estimated to share an increasing proportion of greenhouse gas emissions compared to other sectors in the future. In Europe, inter-regional transport policies place great attention to prevention of global warming and a number of policies are implemented. Japan also stands at the point of developing integrated transport system for a better environmental performance.

There are air transport and Shinkansen high speed railway as the main inter-regional passenger transport system in Japan. The energy consumption of Shinkansen is much more smaller than the air transport and therefore its environmental efficiency is emphasized in many environmental assessment reports etc. However, the basis of the argument is the national average of CO$_2$ emission generated only operational phase. Therefore, the advantage of Shinkansen over air transport may reverse depending on the demand, distance and the newly constructed infrastructure, and therefore these factors call for special consideration.

In Japan, there are 84 airports in the 35 prefectures, and most of the airport construction projects are already completed. On the other hand, Shinkansen stations are located in only 23 prefectures. According to the national Shinkansen network plan, total length is about 6,859 km, but currently operating routes is only 2,176 km. It is about 31% of the planned network (see Figure 1).

For these reasons summarized above, this paper aims to analyze the changes in CO$_2$ emissions and eco-efficiency due to a possible shift from air transport to Shinkansen.

SYSTEM BOUNDARY
In this research, CO$_2$ emissions and eco-efficiency from air transport and Shinkansen are estimated...
by applying LCA method while considering following each attribute.

a) Air transport
1) There are no infrastructure between airports.
   (Thus, maintenance such as the railway is not necessary.)
2) It is operating by the straight route between Origin-Destination pair.
3) The longer airplane cruises, the lower \( \text{CO}_2 \) emissions per passenger-km is.

b) Shinkansen
1) Infrastructure is necessary between OD area
   (Thus, the higher \( \text{CO}_2 \) emissions from infrastructure are allocated in the lower demand of the area.)
2) The OD area cannot be linked linearly because of a geographical factor.
   (Thus, the infrastructure construction needs more length than straight-line.)

On the basis of these characteristics, \( \text{CO}_2 \) from operation of air transport and additional LC-\( \text{CO}_2 \) from newly constructed infrastructure and operation from Shinkansen are compared (see Figure 2).

**INVENTORY ANALYSIS**
**IN CASE OF 500KM LONG CORRIDOR**

In the Tokyo-Osaka corridor which is about 500km long, the LC-\( \text{CO}_2 \) and eco-efficiency of air transport and Shinkansen are estimated. Sensitivity with number of passengers is analyzed as well.

**Method and data**

Life stages considered and includes the below components for each transport system. Life time for each system is assumed to be 60 years, which is the period that the infrastructure will be in use.

a) Air transport
   A \( \text{CO}_2 \) emission factor emitted in flight is 111.37 \([\text{kg-\( \text{CO}_2 \)/Flying-km}])\), which is calculated with reference to the environmental report published from the company between Haneda (Tokyo) and Itami/Kansai (Osaka) international airport. The airplane has a seating capacity of 569 passengers for which the load factor is 65% at the maximum. The average speed is assumed to be 450 [km/h].

b) Shinkansen
   (1) Running
   A \( \text{CO}_2 \) emission factor for running stage is 12.25 \([\text{kg-\( \text{CO}_2 \)/(running-km)/16cars}])\), which is derived from the test results of about 700 series of Shinkansen vehicles\[^2\]. The Shinkansen has a seating capacity of 1,323 passengers and the load factor is 50% at the maximum. The average speed is assumed to be 225 [km/h].

   (2) Vehcles
   \( \text{CO}_2 \) emission factors for Shinkansen vehicle are 150 \([\text{t-\( \text{CO}_2 \)/car}])\) for production stage and 95 \([\text{t-\( \text{CO}_2 \)/car/20years}])\) for maintenance stage, which are derived from the existing studies\[^2\]. The life time is assumed to be 20 years.

(3) Main infrastructure construction
   \( \text{CO}_2 \) emission factors for main infrastructure construction are 7,550 \([\text{t-\( \text{CO}_2 \)/km}])\) for the elevated bridge and 4,160 \([\text{t-\( \text{CO}_2 \)/km}])\) for the tunnel\[^1\]. The ratio of elevated bridge to tunnel length is assumed to be half.

(4) Appurtenant infrastructure construction
   \( \text{CO}_2 \) emission factors for incidental infrastructure construction are 1,500 \([\text{t-\( \text{CO}_2 \)/station}])\) for incidental facilities in each stations and 507 \([\text{t-\( \text{CO}_2 \)/km/double track}])\) for ballast track\[^3\]. One station is established per 50km of the railway line.

**Definition of the eco-efficiency indicator**

An eco-efficiency indicator is defined as the effect or performance of services divided by the corresponding environmental load. This is useful for comparing alternative projects with different performances. Referring to the eco-efficiency indicator proposed for Shinkansen vehicles (see [2]), below equation is formulated here by particularly considering the life time and travel speed as performance indicators.

\[
\text{Eco-efficiency} = \frac{(\text{Transport volume}) \times (\text{Life time travel distance})}{(\text{Amount of time required}) \times (\text{Life cycle environmental load})}
\]

**Estimation results**

Estimated LC-\( \text{CO}_2 \) amount from air transport and Shinkansen associated with levels of demand is shown in Figure 3. This result indicates three important points summarized below.

1) \( \text{CO}_2 \) from air transport is almost constant with number of passengers.
2) LC-\( \text{CO}_2 \) from Shinkansen is inversely proportional to number of passengers.
3) LC-\( \text{CO}_2 \) from Shinkansen is lower than that from air transport for passenger volume approximately 1,200 [passengers/day] or more.

On the other hand, eco-efficiency considering travel speed is estimated for each alternative mode and the
results are presented in Figure 4. The break-even point shifts to around 2,000 [passenger/day] because the travel speed of air transport is about twice as much as that of Shinkansen.

As a result, Shinkansen proves its efficiency over the air transport in terms of LC-CO\textsubscript{2} per passenger-km or eco-efficiency for the projected demand of the new Shinkansen lines, which is 4,000-32,000 [passenger/day].

INVENTORY ANALYSIS FOR EACH INTER-PREFECTURAL OD PAIRS

In this analysis, the policy for demand shift from air transport to Shinkansen is evaluated. Therefore, CO\textsubscript{2} emission reduction generated by such a possible change is analyzed by using real data of transport volume and distance for inter-prefectural OD pairs of existing air transport routes. Hence, the estimation method is different from the one defined in the previous section and will be explained below.

Data used for estimation

a) Volume of Transport

The inter-prefectural transport volume is given over 50 areas\textsuperscript{[4]} but in this study, the CO\textsubscript{2} emissions and eco-efficiency are compared taking into account the OD pairs for 33 areas, where there are the existing air transport routes and Shinkansen stations (including what is planned). If the area has several airports, the whole demand is represented by main airport shown in Figure 1.

b) Distance between inter-prefectural OD pairs

In this analysis, length of the air transport route is defined by the straight distance between each airports and access/egress trip to the airport or the station is omitted. For Shinkansen the length of the route for each OD pair is calculated by the conventional railway network length.

Estimation method

a) Air transport

As the energy consumption of the air transport during landing and take off is very large, the longer the distance, the lower CO\textsubscript{2} is emitted per km. Therefore, the influence of distance is considered by distinguishing between LTO (landing and take-off) and cruising in accordance with IPCC guideline. The fuel consumption \( (W_f) \) is calculated from the general equation \( (2) \) of flying range \( (R) \). Then CO\textsubscript{2} emission is estimated by multiplying \( W_f \) by the CO\textsubscript{2} emission factor 3.15 [t-CO\textsubscript{2}/t of fuel] for jet fuel. The CO\textsubscript{2} emission factor is 2.68 [t-CO\textsubscript{2}/LTO] for LTO.

\[
R = \frac{V}{C} \frac{L}{D} \ln \left( \frac{W}{W - W_f} \right) \tag{2}
\]

Here, \( V \): Cruising speed (=450km/h), \( C \): Fuel consumption rate (=0.75 [kg/kgf/h]), \( L/D \): Lift-drag ratio (=18), \( W \): Take-off weight (=272.2 [t]).

b) Shinkansen

Infrastructure of Shinkansen is considered only when there is new constructions and for the operational stage only the existing vehicles are assumed to operating on the new network.

Estimation result

The changes in CO\textsubscript{2} emission and eco-efficiency due to a shift from air transport to Shinkansen are estimated in Table 1. Below part of the left side of the table shows the change in CO\textsubscript{2} emissions per passenger-km, upper part of the right side gives the eco-efficiency. If the air transport is more advantageous than Shinkansen, it is indicated by A (or A when the difference is large). In the contrary case, it is indicated by S (or S when the difference is large).

The results for CO\textsubscript{2} emission per passenger-km show that, the demand for Tokyo is so large that Shinkansen is almost the only advantageous mode for all the OD pairs that either start or end at Tokyo. In the case of Aichi and Fukuoka, Shinkansen is advantageous for the OD pairs if they are using existing infrastructure, but for the pairs with Shikoku and Hokuruku region where Shinkansen does not exist but is planned, the environmental load generated for constructing the infrastructure is large and therefore air transport is more advantageous. And even for the pairs where there is Shinkansen (e.g. Osaka-Iwate corridor) as the length of the air transport route gets short,
the difference between air transport and Shinkansen is small. The estimated eco-efficiency values show the same trend as \( \text{CO}_2 \) emissions. Eco-efficiency increases in particularly in the OD from Aichi or Osaka region to Shikoku or Kyushu regions.

**CONCLUSION**

This paper proposes a method for identification of lower \( \text{CO}_2 \) mode in inter-regional transport system. The potential for a demand shift from air transport to Shinkansen is examined by substantiating \( \text{CO}_2 \) emissions and calculating the eco-efficiency. The results show that Shinkansen is advantageous in all the regions except for lower demand areas, and also in the planned Shinkansen lines.

**REFERENCES**


