A Systematic Approach for Evaluating Public Transport Systems through LCA

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ABSTRACT
This paper presents a systematic LCA application for evaluating the environmental impacts of public transport systems in the planning phases. System Life Cycle Environmental Load (SyLCEL) approach considers the fact that both vehicle production and infrastructure construction stages of the transport systems should be examined since they generate environmental load throughout the whole lifecycle. Subsequently, an eco-efficiency indicator is defined by incorporating the performances and several types of environmental load of the given transport systems, employing the LIME (Life-cycle Impact assessment Method based on Endpoint modeling). Finally for an elaborate discussion of the real cases, the proposed approach is further applied to various medium capacity public transport systems (LRT, BRT, etc.).

INTRODUCTION
The impacts of passenger transport on environment have been generally explored by the emission reduction per passenger-kilometer for their operating phase. However, ample evidence exists that they further add to the environmental load throughout their construction phases, including vehicle production and procurement of materials, therefore the issue should also be considered for an elaborate environmental assessment.

Life Cycle Assessment (LCA) is a systematic approach that provides a rational basis for estimating quantitatively and individually the environmental load of each life stage of construction of facilities and production of vehicles (material procurement and transport; construction and operating; renewal) on human kind and ecologic system. Therefore, LCA is an appropriate to employ for conducting early-stage environmental assessment of providing passenger transport facilities.

For that reason, this paper proposes a general methodology on the basis of LCA framework for evaluating environmental impacts of the passenger transport systems and further applies to given medium capacity transport systems such as AGT (Automated Guideway Transit); LRT (Light Rail Transit); GWB (Guide Way Bus; See Photo 1), BRT (Bus Rapid Transit; See Photo 2). The estimation is not limited to carbon dioxide (CO₂) and considers the estimation and integration of a number of different environmental load relevant parameters. Notably, the sensitivity analysis for the passenger demand enables the minimisation of environmental load by seeking for the best alternative mode for different level of demands.

METHODOLOGY
Each of the transport systems consists of three main parts, the track system, other infrastructural elements and the rolling stock. The environmental effects through their whole life cycle are evaluated by SyLCEL (System Life Cycle Environment Load) concept as depicted in Fig. 1. Each of these elements is further divided into three life stages of construction/production, operating/use (including maintenance and repair), and disposal. In order to estimate
### Table 1 Evaluated passenger transport systems

<table>
<thead>
<tr>
<th>Line</th>
<th>Railway</th>
<th>AGT</th>
<th>LRT</th>
<th>GWB</th>
<th>BRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (km)</td>
<td>15.4</td>
<td>7.7</td>
<td>10</td>
<td>6.7</td>
<td>10.5</td>
</tr>
<tr>
<td>Proportion of Infrastructure form</td>
<td>Concrete</td>
<td>74%</td>
<td>33%</td>
<td>57%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>-</td>
<td>52%</td>
<td>-</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td>Embankment</td>
<td>26%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tunnel</td>
<td>-</td>
<td>5%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Revetment</td>
<td>-</td>
<td>9%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Energy consumption factor</td>
<td>2.5 kwh/train-km</td>
<td>0.996 kwh/train-km</td>
<td>1.5 litre/train-km</td>
<td>0.33 litre/train-km</td>
<td>0.43 litre/train-km</td>
</tr>
<tr>
<td>Travel speed [km/hr]</td>
<td>38</td>
<td>27</td>
<td>20</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>Passenger transport capacity (one-way)[person/hr]</td>
<td>23,400</td>
<td>7,200</td>
<td>5,040</td>
<td>3,700</td>
<td>3,700</td>
</tr>
<tr>
<td>Capacity [person/train]</td>
<td>520</td>
<td>200</td>
<td>140</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>Peak ratio</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Passenger transport volume (two-way)[person/day]</td>
<td>187,200</td>
<td>57,600</td>
<td>40,320</td>
<td>29,600</td>
<td>29,600</td>
</tr>
</tbody>
</table>

The total environmental load for the construction stage, the environmental load of each element (Fig. 2) is considered as a standardized emission factor of a typical structure and is multiplied by the quantity of each associated element. For the operating stage, the travel length is multiplied by the emission factor of consumption of fuel or electricity (See [1] for more details of the methodology).

Estimated contaminants, carbon dioxide; nitrogen oxides; and sulfur oxides which exert environmental impacts on air pollution, global warming and acidification are further integrated by employing “LIME” (Life Cycle Impact Assessment Method based on Endpoint Modeling) which was developed by Research Center for Life-cycle Assessment in the National Institute of Advanced Industrial Science, Japan.

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

\[
\text{Eco-efficiency} = \frac{\text{Average number of person carried} \times \text{Lifetime travel distance}}{\text{Amount of time required} \times \text{Lifetime environmental load}}
\]
CASE STUDIES

Table 1 gives the basic installation values for each alternative passenger transport mode, examined. Estimated contaminants are carbon dioxide (CO$_2$), nitrogen oxides (NO$_X$), and sulfur oxides (SO$_X$). By employing the methodology described above, and taking transport systems within the metropolitan area of Nagoya city in Japan, environmental load variations are analyzed in relation to demand changes.

INVENTORY ANALYSIS

Infrastructure construction stage

The amount of embodied CO$_2$ emissions for the construction stage is; 8,470[t-CO$_2$/km] for GWB, 9,940[t-CO$_2$/km] for AGT, 11,800[t-CO$_2$/km] for railway. For the railway system, embankments with less potential of environmental load, compared to that of the bridges, covers 25% of the total infrastructure and elevated sections are dominated by concrete bridges which have less environmental impacts compared to steel structure. For GWB and AGT, which have nearly been constructed on bridge structure, generate lower environmental load as a consequence of narrow width of their tracks, despite the high share of steel structure over the whole infrastructure.

SyLCEL evaluation

SyLCEL is computed for each passenger transport system per person-kilometer again for each transport mode and the results are shown in Fig. 3 in terms of CO$_2$. Demand for each transport mode is set as 5000 persons/day and the operating occupancy and number of vehicles required are calculated on the assumption that vehicle passenger-capacity rate is 11.5% (Data base for GWB, 2003).

GWG generates large environmental load not only during the operating stage, but also in the construction stage especially when considering the volume of passengers transported. The environmental load of the construction for LRT and BRT are rather small and their operating stage loads account for almost the total SyLCEL value. When comparing BRT with GWB, fuel consumption of GWB is more economic attributed to better acceleration and deceleration and therefore contributes less to the environmental load in the course of running. Therefore, although the loads from the construction stage of GWB are high these are overwhelmed by the low fuel consumption.

The amounts of SO$_X$ for GWB and AGT are relatively high which may be attributable to the high share of steel construction, having high potential of SO$_X$ generations during production stage, compared to the other passenger transport systems that are mostly constructed as concrete structures. NO$_X$ emissions from the operating of GWB and BRT are also high, because the two systems run by diesel oil which generate more NO$_X$.

IMPACT ASSESSMENT

Each three types of emissions, evaluated, are integrated and converted to monetary terms by employing LIME and the results are shown in Fig. 4 for each passenger transport mode. Among, the largest environmental load is for GWB and is three times as much as that of smallest value for LRT. Upon examining the proportion of each emission contributing to the environmental load, CO$_2$ makes up for almost half of the total combined impacts. This is a very likely reason that even small amount of SO$_X$ and NO$_X$ emissions exert much impact on air pollution. Especially, NO$_X$ is emitted on road and hence environmental impact per unit amount of emission is even larger. Notibly, the integrated monetary value of the three types of emissions is a slight portion of the operating cost and varies for the different transport modes.

It should be noted that the results presented above are estimated based on the structure illustrated in Fig. 1 and therefore they do not apply for the general case of each alternative passenger transport system.

SENSITIVITY ANALYSIS BY DEMAND VARIATIONS

Variations in SyLCEL by the passenger demand changes

SyLC-CO$_2$ (value that appraises CO$_2$ by SyLCEL) rely heavily on the presumed amount of passenger demand. Therefore a sensitivity analysis to measure the impacts of the various demand shifts on the environmental load is appropriate. SyLC-CO$_2$ are estimated.
for different levels of demand and are given in Fig. 5. For the daily passenger demand less than approximately 50,000 persons/day the smallest value of SyLC-CO$_2$ is for LRT; for the demand higher this the least SyLC-CO$_2$ is for AGT, and subsequently when the demand exceeds 100,000 persons/day, the railway takes the smaller value. For each of the five passenger transport modes, SyLC-CO$_2$ per person-kilometer reduces with the increasing demand, but converges to a steady value when the demand increases further, to an extent. This means that environmental loads per person-kilometer, other that those arising from operating stage, approach to zero. In this case, the environmental load depends on the emission factor of vehicle operating; and the average occupancy and the carrying capacity of that vehicle.

For GWB, AGT and railways, SyLC-CO$_2$ firmly decreases until the demand reaches 20,000 persons/day. The environmental load is also very likely to a have decrease in the environmental load even for GWB which has the largest load (Fig. 4). Since almost the whole environmental load by BRT is generated during operating stage, SyLC-CO$_2$ does not vary for an increase in passenger demand.

**Evaluation by an eco-efficiency indicator**

Eco-efficiency by SyLC-CO$_2$ are estimated for each alternative mode and the results are presented in Fig. 6. Highest eco-efficiency values, derived for different ranges of demand are: LRT with the passenger demand less than 12,000 persons/day; and railway for high passenger demand. For every value of passenger demand, the eco-efficiency of GWB is below that of either AGT or railway.

The exchange point of the ranking between BRT and GWB is at 150,000 persons/day for SyLC-CO$_2$ per person-kilometer and at 14,000 persons/day for eco-efficiency. This is the consequence of 1.67 times higher scheduled travel speed for GWB than BRT that is SyLCEL value per person-kilometer is 1.67 time more than the BRT at the turning point where the assumed passenger demand is 14,000 persons/day. Upon comparing AGT to railway, break-even point for SyLCEL per person-kilometer is 100,000 persons/day and for eco-efficiency a much smaller amount of demand, 12,000 persons/day.

**CONCLUSION**

On the purpose of exploring the environmental impacts of passenger transport systems, a systematic approach based on the LCA framework was offered for a comprehensive evaluation in the planning phase. This was further applied to real cases of medium capacity alternative transport modes (AGT, LRT, GWB, BRT) to suggest the passenger transport mode with least environmental load per person-kilometer throughout its whole lifecycle. The findings of the impact assessment were consistent with the fact that not only the CO$_2$ emissions, sharing a very large proportion, but also SO$_x$ and NO$_x$ emissions contributed to environmental load to a large extent. Considering the eco-efficiency which is given by the travel speed and capacity for each alternative mode, high-capacity and high-speed medium demand passenger transport modes were found to have a better performance. Finally it can be concluded that proposed method, considering also the passenger demand level, proved its suitability for environmental performance of passenger transport systems.

**REFERENCES**
