Life Cycle Assessment of Road Improvement Projects Considering Innovations in Vehicle Technology and Changes in Traffic Demand

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Abstract: A life cycle assessment (LCA) framework is applied to evaluate environmental load from road transport systems, including infrastructure and vehicle travel. The results indicate that reductions in the environmental load from improvements in vehicle fuel consumption are greater than the increases due to infrastructure construction and induced traffic, resulting in an overall reduction in the environmental load. This framework provides important results as follows: 1) evaluation of the uncertainty of diffusion of low-CO_2 vehicles and changes in traffic demand, 2) evaluation boundaries that are defined for each scope and definitions of boundaries change the interpretation and uncertainty of the results, and 3) sensitivity analyses test and provide a description of the uncertainty. This framework is applied to the removal of a railway crossing by constructing an elevated track and analyzes the resulting change in CO_2 emissions.

Keywords: Road Improvement Project, Life Cycle Assessment (LCA), Technology Innovation, Sensitivity Analysis

1. INTRODUCTION

Road transport contributes significantly to carbon dioxide (CO_2) emissions. Road improvement projects may be effective to reduce these emissions. Fuel consumption of vehicles becomes more when the number of stops and total idle time increase by congestion as well as by existence of intersections and grade crossings on the roads. Therefore, road improvement projects play an important role in reducing environmental load including CO_2 and are very likely to significantly increase efficiency to reduce environmental pollution.

The impacts of vehicles on the air environment have been generally explored by possible emission reductions for their operational phases, that is, while they are moving. However, additional environmental load is obviously generated during the construction phase of the infrastructure, as well as by generated traffic added through an increase in the level of service after the improvement of the infrastructure. This additional load should also be considered for a more elaborate environmental assessment.

Besides road improvement projects, technology innovation such as improvement of fuel efficiency and low-emission vehicles such as electric vehicles and fuel-cell vehicles are expected to be effective for reduction CO_2 from road traffic (IPCC (2007)).

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 relevant production of vehicles (material procurement and transport; construction and

operation; and renewal). Thus, LCA is appropriate for conducting early-stage environmental assessment for passenger transport project. However, most researches about environmental assessment of road transport do not apply LCA. Some of previous researches quantify the environmental impact of road construction from infrastructure only (Bhandari *et al.*, 2011; Huanga, 2009; Itoya, 2012) or estimates emission from vehicles on the road without considering lifecycle of infrastructure (Aly *et al.*, 2011; Bachmann *et al.*, 2013; Park and Malakorn, 2013). Furthermore, future changes in traffic demand and technology innovation must be included in the LCA framework to increase the effectiveness of decision-making with regard to environmental impact with LCA results. Traffic demand and technology innovation are not currently considered in the LCA framework (Akbarian *et al.*, 2012; Milachowski *et al.*, 2011; Stipple, 2001). It is important to acknowledge that these factors have large uncertainty and will change over the lifetime of infrastructure installations. Nevertheless, such uncertainties have not been given sufficient consideration in LCA for road project. Yu (2012) gives traffic volume as one definite value and considers technology innovation with a few scenarios. Therefore, this study focuses on these two factors and shows how these uncertainties affect the LCA results.

This study applies the LCA framework to evaluate environmental load from road transport systems, including infrastructure and vehicle travel. The method for setting the system boundary for assessment is discussed. Sensitivity analysis is also conducted for different traffic volumes from assumption with technology innovation. These are useful as a methodology to demonstrate the uncertainties of LCA results by assumptions.

2. APPLICATION OF LCA TO TRASPORT SYSTEM

2.1 The Process of LCA

LCA is standardized by the ISO 14040 series guidelines in Figure 1. First, one should set the objective and system boundary (A), then quantify environmental load (B). This result of inventory analysis allows assessment of the environmental impact (C). Finally, results are verified, such as specification of crucial environmental impacts and evaluation of analytical methods (D). This process can be applied to road infrastructure. However, in this paper the environmental load treated in inventory analysis is limited to CO_2 emissions; impact assessment is not provided.
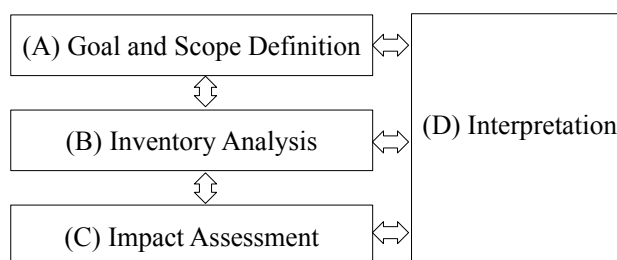

Figure 1. LCA framework standardized by the ISO

2.2 Setting of System Boundary

Construction of infrastructure produces a wide-range of environmental impacts and therefore requires a more systematic approach covering different stages of its whole life cycle. For such a system of evaluation, it is appropriate to employ SyLCEL (System Life Cycle

Environmental Load) and ELCEL (Extended Life Cycle Environmental Load) by and Kato *et al.* (2005). The definition of each system boundary is listed in Table 1. The environmental load from driving vehicles might be greatly reduced through improving driving conditions by mitigating the congestion. This effect is represented by SyLCEL. On the other hand, it is clear that a relief in the traffic will cause an increase in traffic volume either as a result of a shift in time, route and destination, which are called "diverted demand", or as a result of new and longer trips, which is called "induced demand". Therefore, this calls for special consideration of an evaluation through the concept of ELCEL. This is only a small part of ELCEL, in this study called NeLCEL (Network Life Cycle Environmental Load). It is difficult to evaluate ELCEL completely with LCA. This requires another method such as computable general equilibrium (CGE). Generally, the uncertainty increases by setting the system boundary broadly. This study suggests that LCA results should disclose the information of setting the system boundary as in Table 1, and its limitations and uncertainty.

Table 1. Defining system boundary of LCA for road improvement project

System boundary			General road improvement project	Removing the highway rail grade crossing and constructing an elevated rail track system
		LCEL of infra-structure	・Removing existing infrastructure ・Construction of new infrastructure	・Removing the crossing ・Construction of elevated track
		SyLCEL	・Change in driving pattern of vehicles ・Change in systems other than vehicles ・Traffic volume increase in the target section	・Mitigation of congestion and number of stops ・Change in electrical efficiency of train ・Traffic volume increase in the target section
	NeLCEL		・Traffic volume increasing and reallocation to the entire network	・Traffic volume increasing and reallocation to the entire network
ELCEL			・Spread effect to social system such as change in land use	・Spread effect to social system such as change in land use

2.3 Disclosure of LCA results

The uncertainties of assumptions and models in LCA calculation influence LCA results. In particular, LCA at the planning phase of road infrastructure implies input data with large uncertainties because most data are defined by predictions or estimations. It is difficult to build up highly accurate predicted data such as transport demand forecasting. If this is not carefully considered, LCA results can be grossly misinterpreted. This study suggests a way to disclose LCA results with the following information to prevent results from being misinterpreted; 1) to clearly show assumptions for estimation, 2) to show variations in LCA results due to uncertain data by using sensitivity analysis.

3. METHODOLOGY OF LCA FOR ROAD IMPROVEMENT PROJECT

3.1 Quantification of Life Cycle Environmental Load

Road systems consist of two main parts: road infrastructure and vehicles traveling on this road system. Both of these factors should be considered in the framework for quantification of the total environmental load (Figure 2).

This study develops an LCA method for road infrastructure with a virtual road section which has a simple network. When this method is applied to an actual project, it requires

more detailed data collection, such as the difference of traffic volume and speed depending on the day and time.

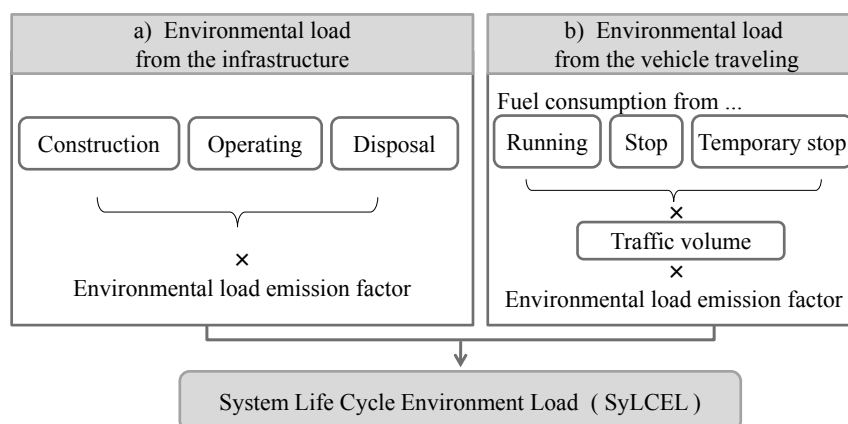The lifetime of this project is assumed to be 30 years. Evaluated environmental load is CO_2 only.

Figure 2. Framework for computing SyLCEL

Table 2. CO_2 emission factors

Type of structure	CO_2 emission
Elevated bridge [t-CO_2/m]	3.10
Elevated station [t-CO_2/station]	3810
Type of fuel	CO_2 emission
Gasoline [kg-CO_2/L]	2.32
Diesel [kg-CO_2/L]	3.66

3.1.1 Infrastructure

Three main life stages of road infrastructure are construction, operation (including maintenance and repair), and disposal. The total environmental load generated by the infrastructure is estimated by using the emission factor for the construction of a elevated railway track (Table 2), as done by Morita *et al.* (2011).

The Railway Technical Research Institute in Japan introduces these emission factors. For the estimation of environmental load from construction, it is desirable to apply the precise data of the structure. However, they are to be implemented in the planning phase in which there is no detailed design of infrastructure. Therefore, it is not realistic to expect precise blueprints or construction plans for this analysis. By this reason, they applied easier measurement with the 'standardized elements' of infrastructure. Infrastructure can be divided into many elements such as bridge, tunnel, station, track, etc. Each individual element is 'standardized' as the most typical form of the structure, which makes it easy to apply the Life Cycle Inventory Analysis. These emission factors include total emission from lifecycle of each element.

3.1.2 Vehicles

Environmental load generated from the driving of vehicles is considered as the fuel consumption during running, stop and temporary stops. Fuel consumption while running is calculated by the function where the parameter is average travel speed, as by Oshiro *et al.* (2001). Then it is multiplied by the emission factor in order to estimate the relevant environmental load. Vehicles are classified as small gasoline car and heavy diesel vehicle. This method is described on equation (1).

$$EL = ELrunning + ELstop + ELtstop \qquad (1a)$$
$$ELrunning = \ \Sigma \,(FCrunning_i * EF_i) * L \qquad (1b)$$
$$ELstop = \Sigma \,(FCstop_i * EF_i) * T \qquad (1c)$$
$$ELtstop = \Sigma \,(FCtstop_i * EF_i) \qquad (1d)$$

Where,

EL: Environmental load emission [kg/vehicle],
$FCrunning$: Fuel Consumption rate of running [l/vehicle/km],
$FCstop$: Fuel Consumption rate of stop [l/vehicle/minutes],
$FCtstop$: Fuel Consumption of temporary stop [l/vehicle/times],
EF: Emission factor of fuel,
L: Length of total road sections [km] (=500m),
T: Time of stop [minutes], and
i: small or heavy vehicle.

Life cycle CO_2 (LC-CO_2) is estimated with this CO_2 emission from one vehicle and traffic volume by equation (2).

$$LC\text{-}CO_2 = EL * Q * 365.25 * LT \qquad (2)$$

Where,

$LC\text{-}CO_2$: Life cycle CO_2 [kg-CO_2],
Q: traffic volume [vehicle/day], and
LT: Lifetime [years] (=30 years).

Emission factor of fuel authorized by Architectural Institute of Japan (2006) is calculated through consumption of resources and manufacturing process (Table 2). Q is allocated by heavy vehicle ratio into small and heavy vehicle.

Equation (1) and (2) shows that CO_2 emission from vehicle driving is determined by fuel consumption rate and traffic volume. Introduction of low-emission vehicles and changes in traffic volume in the future are important uncertainties that will affect those two parameters. Therefore, this study conducts a sensitivity analysis regarding diffusion of low-emission vehicles and traffic volume.

3.2 Diffusion of Low-emission Vehicles

Fuel consumption rate of vehicles (FC) and Emission factor of fuel (EF) in equation (1) are calculated from performance of current vehicles. Diffusion of new technology such as low-emission vehicles affects LCA result.

This study assumes diffusion of a) hybrid vehicles and b) fuel-cell vehicles as low-emission vehicles. These vehicles reduce CO_2 emissions during congestion because they have good fuel efficiency during running and no emissions during stop and temporary stops. Table 3 indicates setting of improving rate of environmental emission factor in low-emission vehicles compared with current gasoline vehicles. The emission factor of driving is determined by reference to results of Well-to-Wheel analysis by Toyota Motor Corporation and MIRI (2004). These are estimations for small vehicles, but this study assumes heavy low-emission vehicles has same ratio of improvement in fuel efficiency. This is because this kind of data about large low-emission vehicles is unavailable.

The future scenario of diffusion of low-emission vehicles is determined by kinds of vehicles, timing of use of each kind of vehicle, and diffusion rate at some point in the future. This study employs the prediction by Matsumoto (2006) in Figure 3, which indicates this scenario: hybrid vehicles grow popular as an alternative to gasoline vehicles, and then a fuel-cell vehicle diffuses from 2020 as an alternative to hybrid vehicles. Finally, in 2030 the diffusion rate of fuel-cell vehicles is 60%. This study deals with the diffusion rate of fuel-cell vehicles after 30 years as uncertain. Figure 4 describes the composition ratio of each kind of vehicle in vehicle-km through 30 years with various diffusion rates.

Table 3. Improvement rate of CO_2 emission factor in each vehicles

(Existing gasoline vehicle=1)

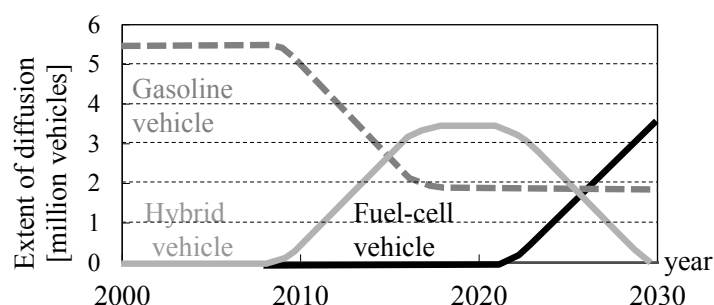|	Running (Well-to-Wheel)	Stop	Temporary stop
Existing gasoline vehicles	1	1	1
Hybrid vehicles	0.47	0	0
Fuel cell vehicles	0.45	0	0

Figure 3. Scenario in diffusion of low-emission vehicles
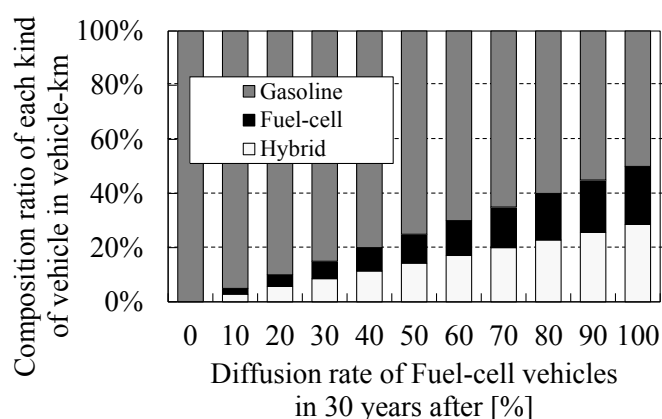

Figure 4. Composition ratio of each kind of vehicle in vehicle-km
through 30 years with various diffusion rates

3.3 Changes in Traffic Demand

As mentioned above, it is likely that a relief in the traffic will cause an increase in traffic demand. This additional traffic demand includes two types of demand: diverted demand as a result of a shift in time, route and destination; and induced demand as result of new and longer trips.

If the additional traffic after improvement is mainly diverted traffic by attracting from other routes, there is a possibility that CO_2 emission from whole road network, which includes the target road section and other routes, is reduced even though SyLCEL, which is emission from only the target road section, increases. This system boundary is called NeLCEL in Table 1. When the effect of diverted demand cannot be disregarded, it is suitable to analyze with System boundary NeLCEL.

This change of traffic demand from before to after the road project is expressed in equation (3) with the model in Figure 5.

$$Q\ NeLCEL_0 = Q_0 + Q'_0 \tag{3a}$$
$$Q\ NeLCEL = Q + Q' \tag{3b}$$
$$= (Q_0 + D + I) + (Q'_0 - D)$$
$$= (Q_0 + \Delta Q) + (Q'_0 - \Delta Q * d / 100)$$

Where,

$Q\ NeLCEL_0$: traffic demand before the project,

$Q\ NeLCEL$: traffic demand after the project,

d: ratio of diverted demand (D) in additional traffic volume(ΔQ) at target road section[%]

This study deals with ΔQ and d as an uncertain parameter and addresses sensitivity analysis for these. For other routes, a Q-V curve enables reflecting a change in average travel speed of vehicles as a result of change in traffic volume in the LCA estimation.
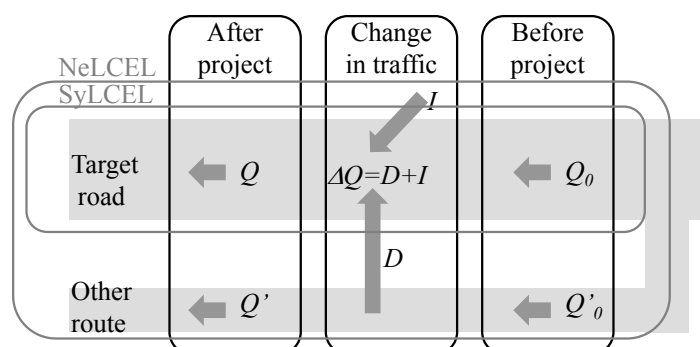

Figure 5. Change in traffic demand between before and after road project

4 CASE STUDY

4.1 Situation and Assumption

The method is applied to a road improvement project, which is the removal of a highway-rail grade crossing and construction of an elevated track system. Figure 6 illustrates the proposed improvement project. There is a 2.1km length of railway, one station and seven crossings. Elevated track is 10m high after the project. The total road section considered is 500m to each grade crossing.

Closing time as grade crossing characteristics and the traffic conditions before and after the removal is defined as Table 4. Crossing A is "Less-opened crossing", which means that the grade crossing is closed to highway for more than 40 minutes at peak hours. And it has heavy

traffic. Crossing B has normal crossing time and traffic volume. The objective period of time is from 7:00 AM to 7:00 PM.

Figure 7 illustrates the driving of vehicles before the crossing. If the crossing closes, stopping vehicles drive only 30 [km/h] and stop and have idling time at the line end, and after the crossing opens, vehicles drive 20 [km/h] and have a temporary stop before entering the crossing. If the crossing opens, passing vehicles drive 40 [km/h] smoothly and have a temporary stop before entering the crossing. In Table 4, length of line, percentage of passing/stopping vehicles and stopping time at the crossing are unavailable as actual measured values. These parameters are set with the help of Webster's delay model.
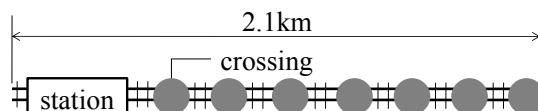

Figure 6. Outline of case study

Table 4. Time of closing railway condition and vehicle traveling conditions

	Crossing A		Crossing B	
	Peak hours	Normal hours	Peak Hours	Normal hours
Average closing time per hour [minutes / hours]	42	24	24	12
Average closing time per one time [minutes/ time]	3	2	2	1
Traffic volume of each crossing [vehicles/12h]	7,000	7,000	5,000	5,000
Heavy vehicle ratio [%]	16	16	16	16
Average queue length [m]	290	140	50	24
Average stopping time [minutes]	4.7	1.0	1.0	0.5
Share of stopping vehicle [%]	100	70	50	30

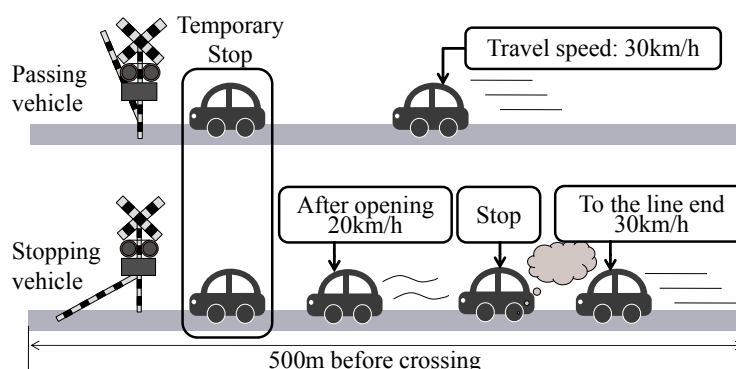Peak hours: 7 AM-9 AM, Normal hours: 9 AM-7 PM

Figure 7. The driving of vehicles before crossing

4.2 Life Cycle CO_2 of Infrastructure

Morita *et al.* (2011) offers an emission factor in elevated rail track and station. They have estimated CO_2 emission from resources, construction and transportation of structures. CO_2 emission by the consumption of resources is summed up from each structure, which is calculated by multiplying the quantity of resources and its CO_2 emission factor. In this case, 'consumption' means collection and refinement of materials. CO_2 emission in construction is the fuel consumption of machines, CO_2 emission by the transportation of resources is the fuel

consumption of transporters. Meanwhile, maintenance and disposal haven not been estimated in this study, because there are not enough examples of maintenance of elevated track and Inamura *et al.* (2002) shows CO_2 emission from disposal is much less than in other phases.

The result is shown in Figure 8. The emissions generated by resources account for about 77% of the total CO_2 from infrastructure.
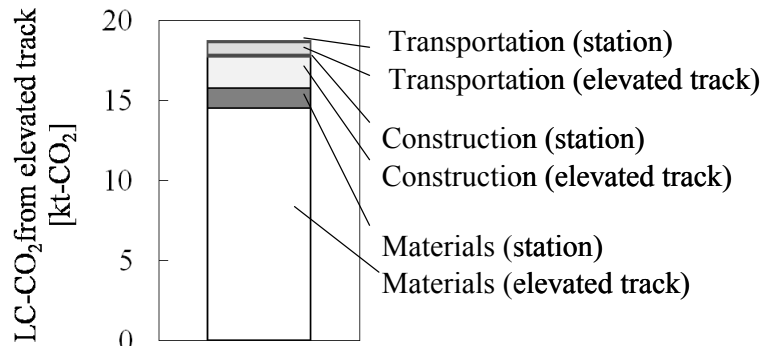

Figure 8. Life cycle CO_2 of elevated track

4.3 Evaluation of Transport System Including Diffusion of Low-emission Vehicles

SyLC-CO_2 (relevant indicator that computes and evaluates CO_2 emissions by SyLCEL) is estimated and the results both for before and after the road improvement are shown in Figure 9. It also provides SyLC-CO_2 in the case that low-emission vehicles diffuse as a scenario in Figure 3 and the case in which only the existing gasoline and diesel vehicles are used throughout the lifetime. The target road section has 7 crossings and 1 station; the graph demonstrates SyLC-CO_2 per one crossing.
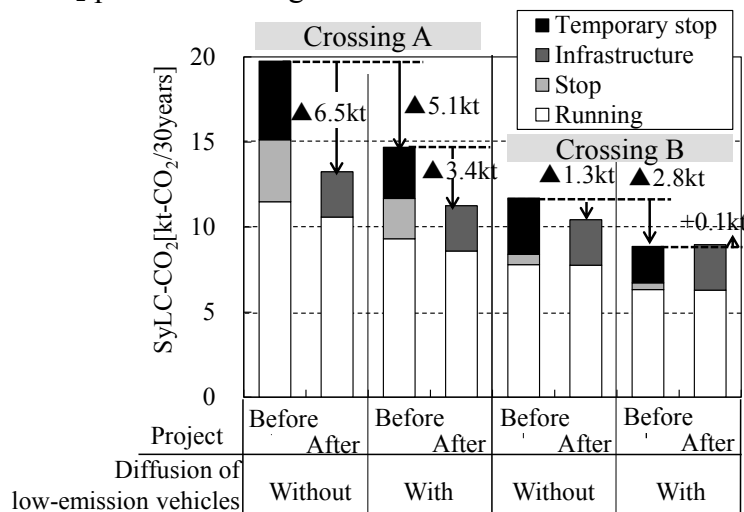

Figure 9. SyLC-CO_2 with and without diffusion of low-emission vehicles

The emissions generated by the driving of vehicles account for about 70% of the total SyLC-CO_2. Diffusion of low-emission vehicles has a significant effect on the result. At crossing A which has heavy traffic and a long closing time, the result without considering diffusion of low-emission vehicles shows that SyLC-CO_2 is reduced about 6.5 [kt-CO_2/30 years]. On the other hand, the result with diffusion of low-emission vehicles shows that

SyLC-CO_2 is reduced 5.1 [kt-CO_2/30 years]. SyLC-CO_2 is reduced after the construction of the elevated track through reducing the number of stops and mitigating the congestion. This effect is less for low-emission vehicles than for existing gasoline vehicles. If the diffusion of low-emission vehicles are not considered, it causes an over estimation of CO_2 reduction. Furthermore, at crossing B, which has normal traffic volume and closing time, the case without considering low-emission vehicles reduces CO_2, while the case with considering low-emission vehicles increases CO_2. Hence, this road project may increase SyLC-CO_2 under the diffusion of low-emission vehicles.

4.4 Sensitivity Analysis with Changes in Traffic Demand

Since LC-CO_2 relies heavily on the amount of traffic volume, a sensitivity analysis that substantiates and compares the impacts of the various volumes of traffic demand on the environmental load is a very important way of gaining insight into environmental efficiency. LC-CO_2 is estimated for different levels of traffic volume after the elevated track project is completed. In this analysis, whether additional traffic volume is induced demand or diverted demand is considered. Since considering diverted demand means that the system boundary covers the road constructing network with the target road section, the result can be called NeLCEL. For induced demand it is assumed that the average trip length is 10km. Diverted demand is from one road in parallel with the target road, as in Figure 5. This road is assumed to be the same length as the target road and is called "other route".

In other route, diversion of traffic decreases CO_2 by relief of congestion. A diversion of traffic from a more congested section to the improved section will obviously contribute to the reduction of traffic on this unimproved congested section. The Q-V curve, which represents the relation between traffic volume and velocity of vehicles, of other route enables analysis of this change, but there is no actual measured data because this case study estimates for a virtual road section. A simplified Q-V curve is made from two plots; [traffic volume = 0, regulatory speed] and [traffic volume in peak time, travel speed in peak time] by Imanishi *et al.* (2008). This case study sets each parameter in Figure 10 with reference to Road traffic census (2005).

Figure 11 shows that NeLC-CO_2 (a relevant indicator that computes and evaluates CO_2 emissions by NeLCEL) is estimated for different levels of $\varDelta Q$ in the equation (3) which means change in traffic volume between before and after project. This figure assumes that $\varDelta Q$ follows three patterns by using parameter d in the equation (3); 1) $d = 0$ which means all of additional volume is induced demand, 2) $d = 50$ which means half of $\varDelta Q$ is induced demand and the other half of $\varDelta Q$ is diverted demand, 3) $d = 100$ which means all of $\varDelta Q$ is diverted demand. If all of additional volume is induced demand (d=0), NeLC-CO_2 increases linearly with increasing traffic demand. On the other hand, if additional demand is from other route (d=100), NeLC-CO_2 decreases with increasing traffic demand for mitigation of congestion in other route. This analysis shows that a mitigation of congestion in other route by diverted demand influences change in NeLC-CO_2 with change in traffic demand.

Figure 11 clearly shows 'switch-point' which means how much amount of change in traffic volume switch the result in reducing NeLC-CO_2 to increasing it. If all of additional volume is diverted demand (d=100), NeLC-CO_2 increases regardless of the amount of traffic volume. If all of the additional volume is induced demand (d=0), NeLC-CO_2 increases by the project with an additional 160 [vehicles/12h]. If additional volume consists of both induced and diverted volume, NeLC-CO_2 increases with less additional traffic volume than the case of d=0. For example, in the case of d=50, NeLC-CO_2 it increases with additional 350 [vehicles/12h].

As above, there is possibility of reduction of NeLC-CO_2 by mitigation of congestion in the whole road network, even if traffic volume increases in the target road section.
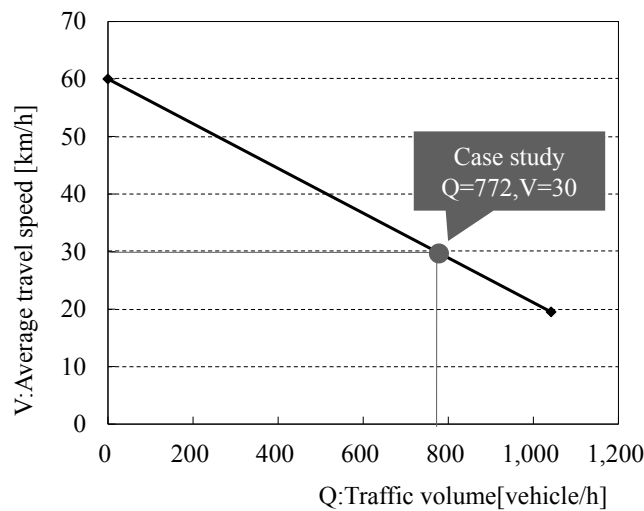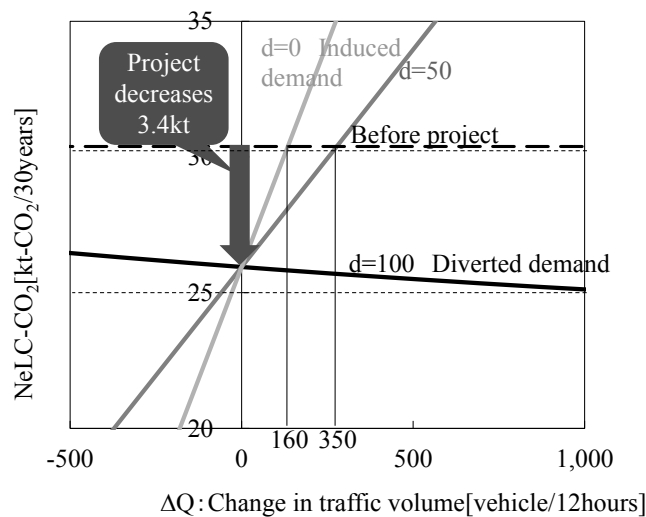

Figure 10. Q-V curve in other route

Figure 11. Sensitivity analysis with change in traffic demand for crossing A

4.5 Influence of Dispersion of Input Variables on Results

The results of the sensitivity analysis in the preceding section are useful for discussing and managing the uncertainty of LC-CO_2. This study describes uncertainty in relation to each assumption for diffusion of low-emission vehicles, shown in Figures 12 and 13. These figures show dispersion width between maximal and minimal values caused by differences in assumptions in LCI and sensitivity analysis results. Figure 12 indicates that the amount of CO_2 reduction depends on the diffusion rate of fuel cell vehicles. It shows that CO_2 reduction is affected by the diffusion rate assumption. For example, if CO_2 is estimated assuming that the diffusion rate will be 0%, the results indicate that a project could reduce 6 [kt-CO_2/30years]. Under the assumption that the diffusion rate will be 100%, CO_2 reduction is only 1.5 [kt-CO_2/30 years]. Figure 13 provides switch points for different diffusion rate assumptions. Here switch point is the point at which change in traffic volume switches the result from reducing to increasing NeLC-CO_2. The switch point in the scenario in which the

diffusion rate equals 0% can be found by locating the point where the top of the dispersion width of each line intersects. The bottom of the dispersion width indicates the result for the scenario in which the diffusion rate equals 100%. The switch point is also affected by the diffusion rate assumption. If the goal of policy makers is to ensure that the project reduces CO_2, allowable ΔQ increases as the diffusion rate increases. However, if ΔQ exceeds approximately 200 [vehicle/12 h], the project would not reduce CO_2 however much low-emission vehicles are used.
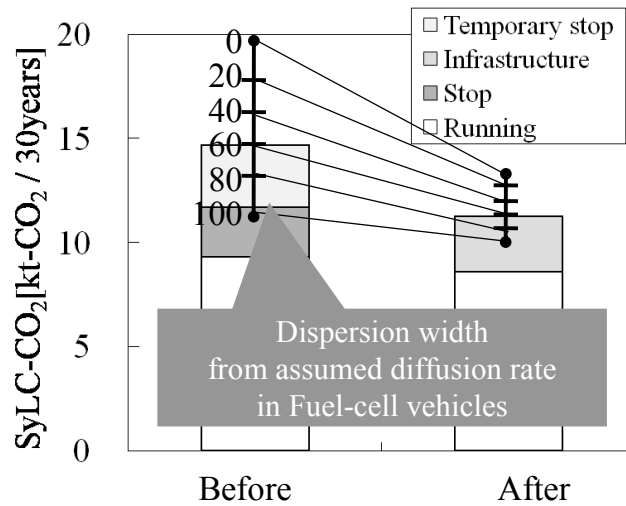
Figure 12. SyLC-CO_2 with dispersion width from assumed diffusion rate in low-emission vehicles
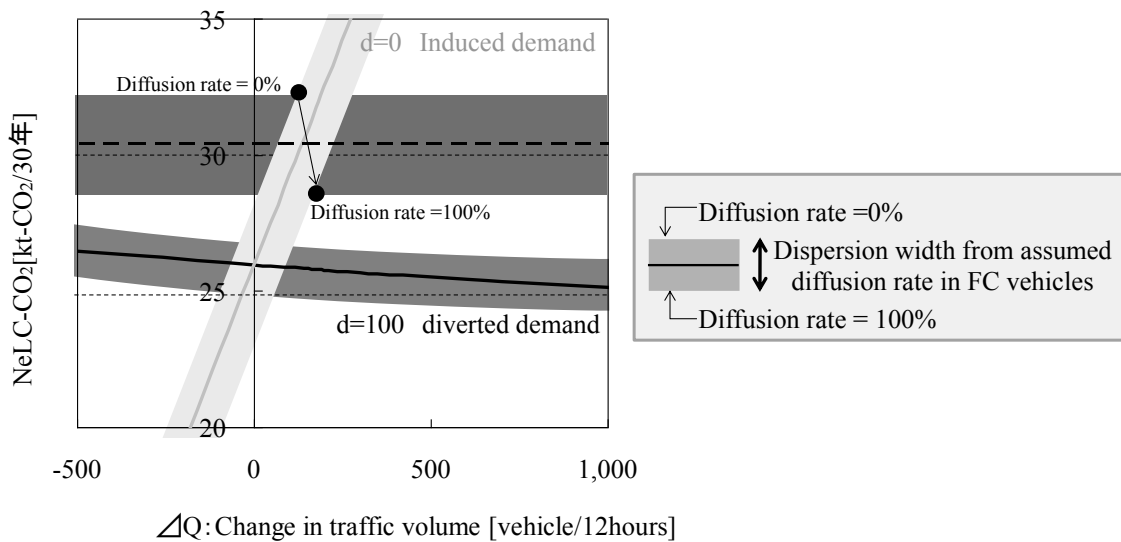
Figure 13. The result of sensitivity analysis with dispersion width from assumed of diffusion rate in low-emission vehicles

5. CONCLUSION

This study applies the LCA framework to evaluate CO_2 from road transport systems, including infrastructure and vehicle travel. In particular, this methodology considers the following two points:

1) The system boundary is classified step-by-step according to scope. Suitable interpretation is discussed for each system boundary.
2) The sensitivity analysis is conducted for different traffic volumes from assumption for calculation or technology innovation in the future. This analysis provides intervals of LCI results and switch-points. These help to discuss the adequacy of the assumptions and uncertainties of the results.

This methodology was applied to a case study of removing the highway rail grade crossing and constructing an elevated rail track system. A case study clearly shows that this methodology includes the mechanism which cannot be analyzed with the existing LCA framework as follows;

1) Without diffusion of low-emission vehicles, CO_2 is reduced by the road improvement project. Though constructing infrastructure increases CO_2, mitigation of congestion decreases much more CO_2 from vehicles.
2) Meanwhile in the case of diffusion of low-emission vehicles considerably, SyLC-CO_2 may increase. Because low-emission vehicles have less effect of CO_2 reduction by mitigation of congestion, it is likely that additional CO_2 from construction infrastructure will be much more than the CO_2 reduction of vehicles.
3) If additional volume is from other routes, NeLC-CO_2 decreases with increasing traffic volume for mitigation of congestion on other route. On the other hand, if additional volume in the target road section is induced demand, NeLC-CO_2 increases linearly with increasing traffic volume.

In Asian mega-cities, traffic congestion is a serious problem. These results indicate that road construction and improvements will be effective countermeasures. When policy makers study the extent to which a road project could reduce environmental load, this LCA method would be helpful. In addition, it is particularly difficult to predict future traffic demand and diffusion of low-emission vehicles in Asian countries that have achieved rapid economic development. The sensitivity analysis proposed in this study can contribute to decision-making under such uncertain situations.

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REFERENCES

Akbarian, M., Moeini-Ardakani, S. S., Ulm, F., Nazzal, M. (2012) Mechanistic Approach to Pavement–Vehicle Interaction and Its Impact on Life-Cycle Assessment, *Journal of the Transportation Research Board*, No.2306, pp.171-179.

Aly, S., H., Selintung, M., Ramli, M., I., Sumi, T. (2011) Study on Emission Measurement of Vehicle on Road Based on Binomial Logit Model, *Journal of the Eastern Asia Society for Transportation Studies*, Vol.9, pp.784-795.

Architectural Institute of Japan (2006) LCA data base ver.4.04.

Bachmann, C., Chingcuanco, F., MacLean, H., Roorda, M. J. (2013) Life Cycle Assessment of Cooperative Vehicle Infrastructure Systems, *Proceedings of Transportation Research Board 92nd Annual Meeting*, CD-ROM

Bhandari, K., Shukla, A., Gangopadhyay, S. (2011) Carbon footprint: a tool to quantify the impact of road construction on the environment, *Journal of the Eastern Asia*

Society for Transportation Studies, Vol.9, pp.740-755.

Huanga, Y., Birdb, R., Bellb, M. (2009) A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation, *Transportation Research Part D: Transport and Environment*, Vol.14, No.3, pp.197-204.

Inamura,H., M.Piantanakulchai., Takeyama,Y. (2002) Life Cycle Inventory Analysis of Transportation System - Comparative Study of Expressway and Shinkansen -, *Transport Policy Research Review*, Vol.4 No.4 2002 Winter, pp.11-22. (in Japanese)

Intergovernmental Panel on Climate Change (IPCC) (2007) IPCC Fourth Assessment Report -Working Group III Report "Mitigation of Climate Change", pp.325-380.

Imanishi,Y., Ishida.H., Kakei,F. (2008) A study on the short-term changes of traffic volume and CO_2 emissions after building highways, *Traffic Engineering*, Vol.43 No.3, pp.53-63. (in Japanese)

Itoya, E., Hazell, K., Ison, S., El-Hamalawi, A., Frost, M. W. (2012) Framework for Carbon Emission Evaluation of Road Maintenance, *Journal of the Transportation Research Board*, No.2292, pp.1-11.

Kato, H., Shibahara, N., Osada, M. (2005) A Life Cycle Assessment for Evaluating Environmental Impacts of Inter-regional High-speed Mass Transit Projects, *Journal of the Eastern Asia Society for Transportation Studies*, Vol.6, pp.3211-3224.

Matsumoto, M. (2006) AIST TODAY, vol.6, No.12, pp.16-17. (in Japanese)

Ministry of Land, Infrastructure and Transport (2005) Road traffic census. (in Japanese)

Milachowski, C., Stengel, T., and Gehlen, C.(2011) Life Cycle Assessment for road construction and use, European Concrete Paving Association, Brussels

Morita, Y., Shimizu, K., Yamasaki, T., Kato, H. (2011) A Study on Greenhouse Gas Emission of Urban Railway Projects in Tokyo Metropolitan Area, *Proceedings of the Eastern Asia Society for Transportation Studies*, Vol.8, CD-ROM(100149).

Oshiro, N., Matsushita, M., Namikawa, Y., Ohnishi, H. (2001) Civil engineering journal, Vol.43, No.11, pp. 50-55. (in Japanese)

Park, B., Malakorn, K. J. (2013) Life Cycle Assessment of Cooperative Vehicle Infrastructure Systems, *Proceedings of Transportation Research Board 92nd Annual Meeting*, CD-ROM

Stipple, H. (2001) Life Cycle Assessment of Road -A Pilot Study for Inventory Analysis, IVL Swedish Environmental Research Institute Report.

Toyota Motor Corporation and Mizuho Information & Research Institute (MIRI) (2004) Well-to-Wheel Analysis of Greenhouse Gas Emissions of Automotive Fuels in the Japanese Context - Well-to-Tank Report -, p.3.

Yu, B., Lu, Q. (2012) Life cycle assessment of pavement: Methodology and case study, *Transportation Research Part D: Transport and Environment*, Vol.17, No.5, pp.380-383.