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.

$$Q\ NeLCEL_0 = Q_0 + Q'_0 \tag{3a}$$

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

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.

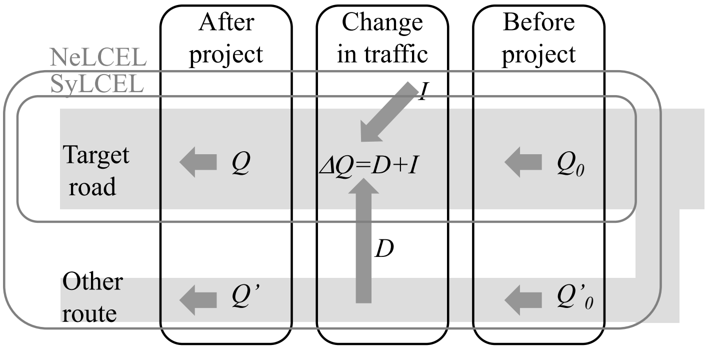

Figure 5. Change in traffic demand between before and after road project

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.

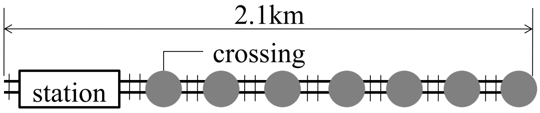

Figure 6. Outline of case study

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

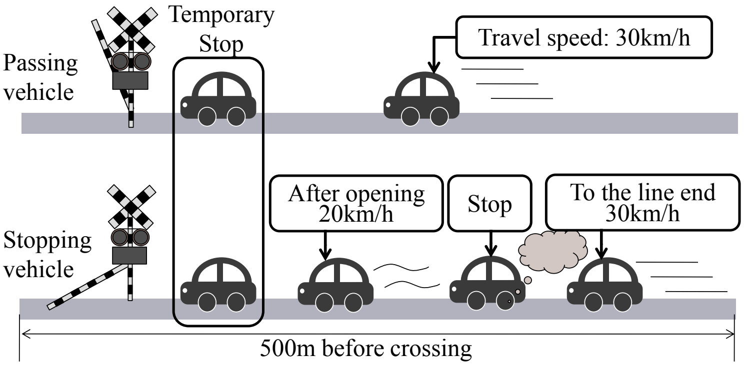

Figure 7. The driving of vehicles before crossing

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.

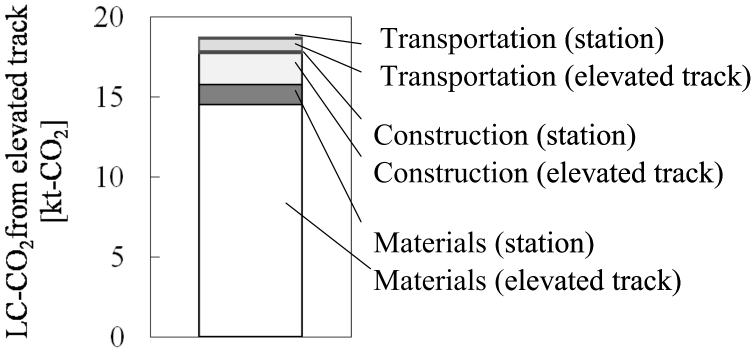

Figure 8. Life cycle CO_2 of elevated track

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.

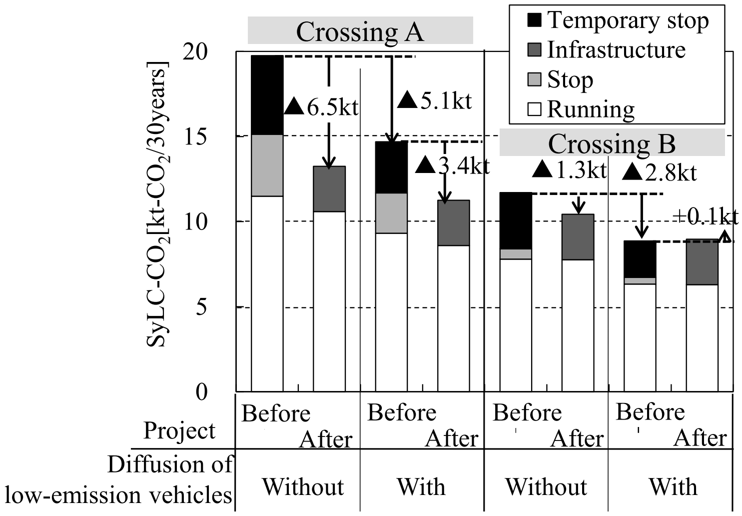

Figure 9. SyLC-CO_2 with and without diffusion of low-emission vehicles

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 ΔQ in the equation (3) which means change in traffic volume between before and after project. This figure assumes that ΔQ 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 ΔQ is induced demand and the other half of ΔQ is diverted demand, 3) $d = 100$ which means all of ΔQ 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.

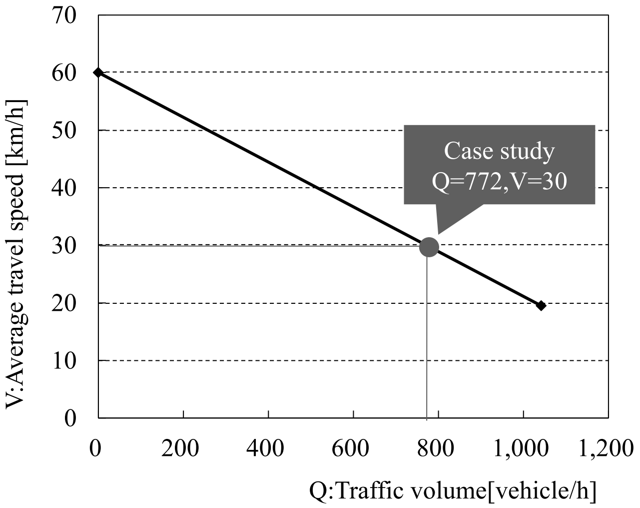

Figure 10. Q-V curve in other route

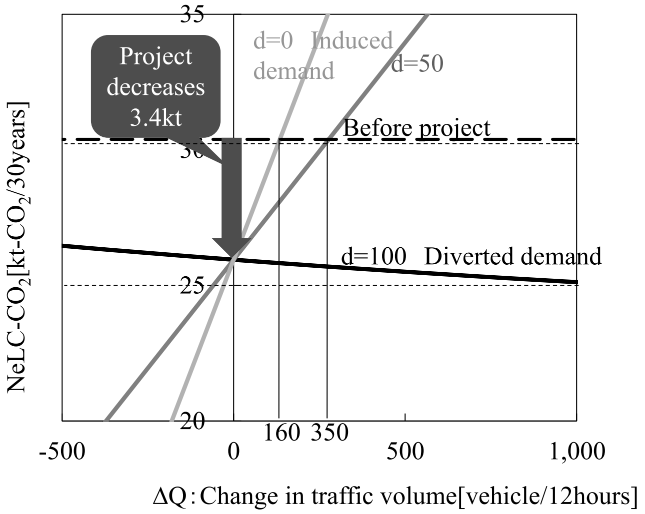

Figure 11. Sensitivity analysis with change in traffic demand for crossing A

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.

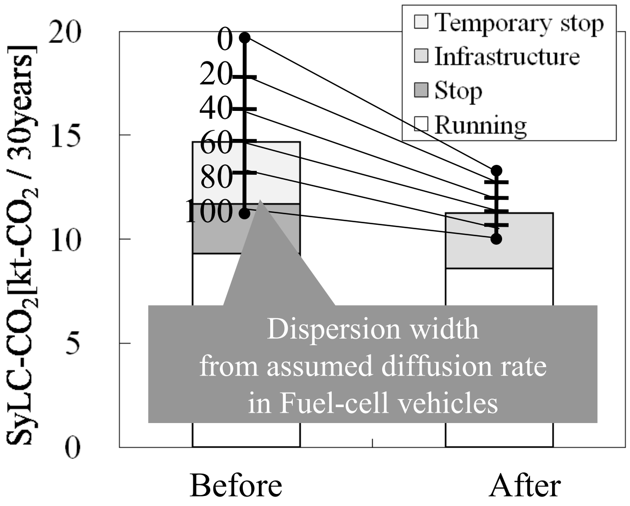

Figure 12. SyLC-CO_2 with dispersion width from assumed diffusion rate in low-emission vehicles

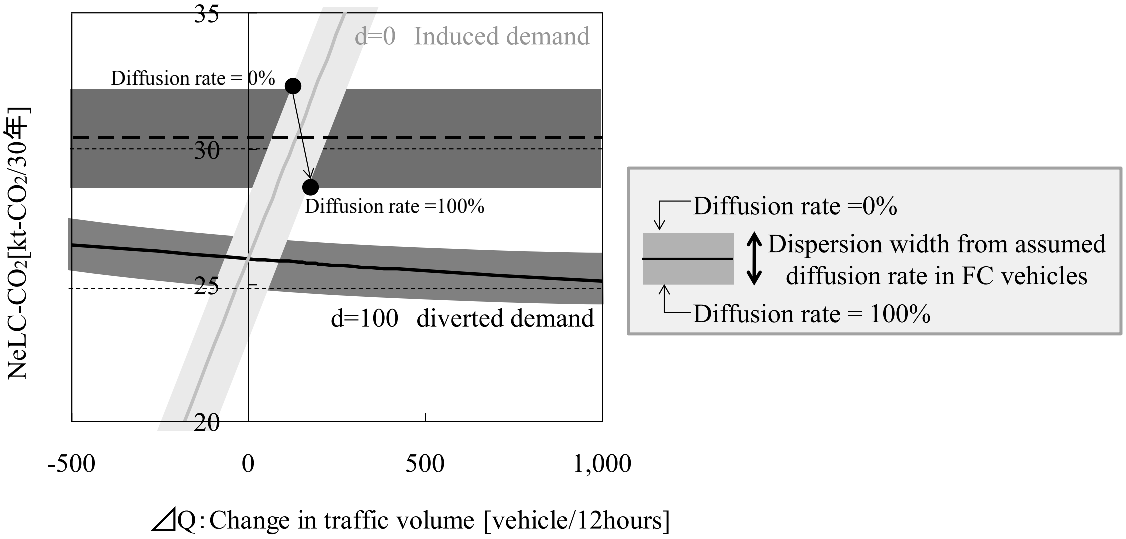

Figure 13. The result of sensitivity analysis with dispersion width from assumed of diffusion rate in low-emission vehicles

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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