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Dynamic techno-ecological modeling of highway systems: a case study of the Shin-Meishin Expressway in Japan

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ABSTRACT

The Shin-Meishin Expressway is being constructed from Nagoya to Kobe in Japan, and the section from Takatsuki to Kobe is currently under construction as a viable alternative route as opposed to the Meishin Expressway. However, highway construction is usually considered destructive to the natural environment due to the deforestation required during construction, as well as subsequent increases in CO_2 emissions upon completion of new highways as new traffic is brought to the area. By applying a system dynamics methodology with respect to the Meishin and Shin-Meishin Expressways, this study analyzes two major effects of new highway construction (CO_2 absorption and CO_2 emissions) as well as the potential influence of felling, replanting, and/or maintaining the surrounding forest area on the overall CO_2 absorption capacity, net CO_2 emissions, and total CO_2 stock in the analyzed construction area. Regarding CO_2 absorption, it was found that, if the portion of the forest felled during construction is very old, new highway construction can help to recover the lost CO_2 absorption capacity by planting new trees along the highway, even if the area of planting is much smaller than the area of felling trees. As for CO_2 emissions, it was found that mitigating traffic congestion and decreasing the required driving distance can reduce CO_2 emissions from the highway(s) in question. Therefore, this study concludes that new highway construction does not always harm the environment regarding CO_2 pollution, as the harmful impacts commonly associated with highway construction can be mitigated with other technological and/or ecological mitigation methods.

1. Introduction

1.1. Human/ecology interaction and the transportation sector

Although the origins of environmentalism date as far back as the 19th century, with prominent examples of environmental destruction by human activities going back even further, the beginnings of the environmental movement as a significant influence on global policy-making are still relatively recent, with its greatest accomplishments starting in the 1960s (McCormic, 1989). Even today, while there have been significant advances in the various methods and technologies used to address environmental concerns, current environmental solutions still generally tend to rely on technological systems and applications to treat and/or minimize pollution, while the potential of natural ecosystems and other ecologically-based solutions to sustain and enhance the benefits of these technological solutions is often neglected (Urban and Bakshi, 2013). In the transportation sector, for example, road and highway infrastructure has been known to seriously impact nearby ecosystems directly and indirectly in several different ways, including the deforestation and/or hydrological disruption resulting from construction of a particular roadway, as well as the subsequent levels of noise, air, and water pollution resulting from use of the roadway (Coffin, 2007). However, the inclusion of environmentally synergistic elements (a.k.a. green infrastructure) in the design of a given roadway, such as the planting and/or management of nearby forest habitats for carbon sequestration or the use of man-made wetlands near the roadway to manage and treat stormwater runoff, have been proven to significantly mitigate these environmental impacts by using the natural environment as an effective tool, and provide a wide variety of social and economic benefits as well (Naumann et al., 2011), though these relatively simple possible solutions are not commonly used in practice. For this study, the currently ongoing construction of the Shin-Meishin Expressway in Japan as

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an alternative route to the existing Meishin Expressway will be used as a case study to analyze the potential of the new highway to mitigate CO_2 emissions from the highway system as a whole, and particular emphasis will also be given to CO_2 absorption capacity losses and gains from the felling, restoration, and maintenance of the local forest area surrounding part of the planned construction area, as well as CO_2 emission reductions from technological innovations and improved fuel efficiencies for the vehicles traveling along the roadway system.

1.2. Study area and research objectives

The Shin-Meishin Expressway is currently being constructed from Nagoya to Kobe in Japan, and from Toyota JCT to Kobe JCT, this new route is about 40 km shorter than the existing Meishin Expressway (Fig. 1). The Meishin Expressway, which was opened to traffic in 1963, was the first expressway in Japan, and has one of the heaviest traffic volumes among Japanese expressways today. Consequently, damages to structures in the route have become more and more frequent with each passing year, but since there is no alternative highway route, and because the Meishin Expressway remains an indispensable network for logistics and economy, it has been impossible to do major repair work, rehabilitation, and/or replacement with long-term lane closure (NEXCO-West, 2012). On the other hand, the Shin-Meishin Expressway is expected to become a viable alternative route as opposed to the Meishin Expressway. The effects of the proposed new route have been assessed for various impacts, such as the mitigation of traffic congestion on the existing route, a decrease in required travel distances and times, development of the surrounding area, and reduction of environmental loads (NEXCO-West, 2012). However, regarding environmental impacts (especially CO_2 reduction), the impacts of the proposed new route have not yet been considered in terms of stocks and flows. In this paper, two primary impacts of the proposed new highway construction are evaluated with the system dynamics (SD) simulation method and with the modeling software VENSIM: (1) the impact on CO_2 absorption from construction in the Osaka area (Fig. 1), and Fig. (2) the impact on CO_2 emission from construction between Tkatsuki JCT and Kobe JCT (Fig. 1). Due to limited data and information availability, the scope of the evaluation must be adjusted accordingly.

The field of SD was first introduced in 1956, and is still in development today. SD uses computer simulations to help decision makers better understand the behavior of social systems over time (Forrester et al., 1976). For this reason, SD deals primarily with systems that are too complex for a direct mathematical analysis by integrating knowledge from various fields (science, psychology, politics, biology, environment, economics, management, etc.) with concepts of how feedback structures cause changes to the system through time (Forrester, 1992). SD is a powerful tool that has been used to model complex systems to understand the pattern of behavior of different stages over time, and can also simulate various proposed policies and their effects on the modeled systems in order to see the impacts of these policies on system behavior and compare the results with a baseline ("do nothing") scenario, allowing for the development of SD models to aid in future decision making for various fields (Egilmez and Tatari, 2012).

2. Literature review

2.1. Review of similar topics and studies

The case study to be evaluated in this paper is an example of a possible application of techno-ecological synergy, with the construction of the new highway being evaluated individually and in tandem with technological solutions (inclusion of low-emission and zero-emission vehicles) and ecological solutions (management of local urban forest area) with respect to CO_2 reduction potential. Although the idea of techno-ecological synergy as a system design/analysis methodology is still relatively new in practice and few studies on techno-ecological synergy in general were available, extensive studies on such synergistic systems were found among existing literature. For example, in his dissertation at the Ohio State University, Urbana (2012) thoroughly described and evaluated the importance and potential benefits of explicitly accounting for available ecosystem benefits in the design process for various applications, including demonstrations of techno-ecological synergy applications for typical suburban homes and comparisons of alternative fuels with ecologically-based life-cycle assessment and energy analysis. A similar dissertation by Grubb (2010) focused on the environmental analysis and improvement of manufacturing systems with particular emphasis on the Nano manufacturing industry, including the design of "carbon conscious" techno-ecological networks and reviews of associated case studies. In two separate publications, Zhang addressed the inclusion of natural ecosystems in life cycle assessment to encourage sustainable development, first by

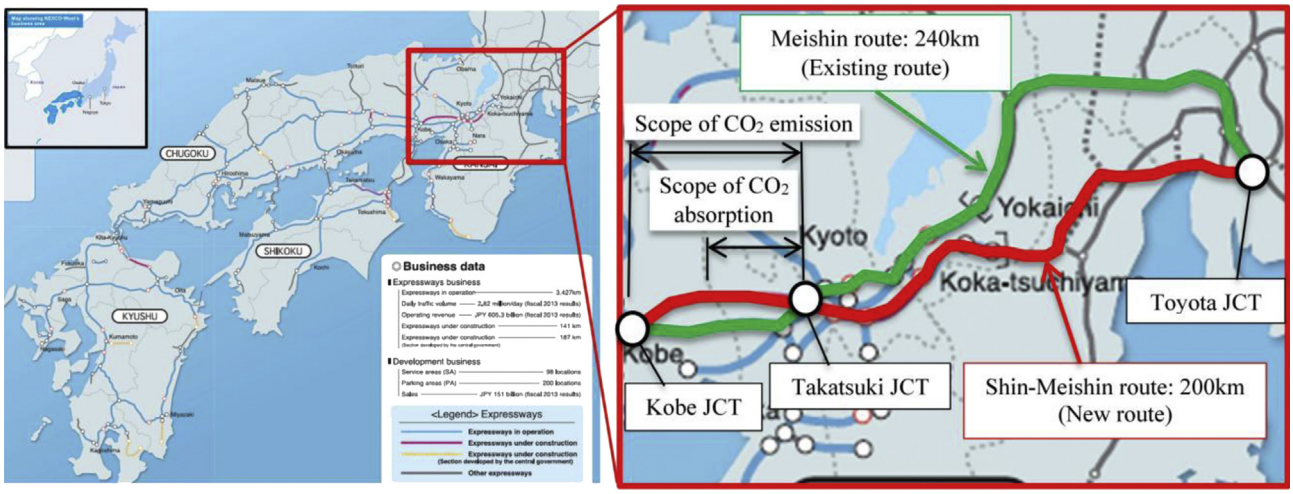

Fig. 1. Location of the Shin-Meishin Expressway (Source: (NEXCO-West, 2014a)).