Network Impact Evaluation of the Introduction of Road and Rail to a Transport Corridor for Developing Cities

Peng Jia*  Hirokazu Kato**  Yoshitsugu Hayashi***

* D. Eng. Candidate, Graduate School of Engineering, Nagoya University E-mail: jiapeng@urban.env.nagoya-u.ac.jp (corresponding author)
** Associate Professor, Graduate School of Environmental Studies, Nagoya University E-mail: kato@genv.nagoya-u.ac.jp
*** Professor, Graduate School of Environmental Studies, Nagoya University E-mail: yhayashi@genv.nagoya-u.ac.jp

This paper analyzes the global network impact of the introduction of new transport infrastructure involving road and rail to a transport corridor. The analytical framework is proposed by transport network-based simulation. Transport network is composed of road network, bus network and rail network. Both passenger demand and freight demand are considered. Four scenarios are built, including do-nothing, the introduction of both road and rail, the introduction of only road and the introduction of only rail. Each representative scenario is evaluated from three aspects viz., efficiency, equity and environment. A case study of the city of Dalian, China is conducted to address the difficult trade-off issue. The results show that as car ownership or passenger demand increases the changing trend for each indicator is distinct. The findings have significant implications for other developing cities.

Keywords: road, rail, efficiency, equity, environment
1. INTRODUCTION

Developing cities are suffering from the decline of transport efficiency and the deterioration of environmental quality due to the rising car ownership. The introduction of the new infrastructure, road or rail, in the transport corridor can be regarded as an optional measure to improve this situation. The role of road cannot be ignored in regards to private car traffic, road network accommodates dominant public bus traffic and freight truck traffic. But traffic congestion caused by the induced traffic and the accompanying emissions on roads are not consistent with sustainable development principles. Compared to road, rail is regarded as an environment-friendly infrastructure due to the electricity-powered train. But the level of service of rail depends on its feeder system like the bus system, which depends on the level of service of the road system. Also, the developing cities cannot support a dominant rail network covering the entire region to a desired extent. Obviously, it leads to a decision making dilemma involving a trade-off between road and rail. To deal with this issue, it is necessary to analyze the impact of the introduction of road or rail in the transport corridor on the transport network. Such an evaluation will give significant implications for building a sustainable transport system, especially for developing cities.

However, to our knowledge, such analysis is rarely taken into account in any presently available literature. Most of the studies just conducted network analysis on the introduction of only a type of infrastructure, the road or the rail, separately. Santos et al. (2008) conduct the evaluation of different equities for road network design models. Szeto and Lo (2009) focuses on analyzing the aspect of cost recovery with consideration of time dimension for road network design models. Keshkamat et al. (2009) present a spatial multi-criteria network analysis method for transport route planning alternatives in a network of existing roads. Jia (2007) present a road alignment optimization model considering network impact analysis. Peng (2007) propose a rail network design model in an inter-modal network. Jha et al. (2007) study a rail alignment optimization approach. They evaluated the network impact for the introduction of rails. Bhandari et al. (2008) present a case study in Delhi to address the issues on the mobility and the equity for the introduction of a new rail system by the revealed preference method. Han and Hayashi (2008) evaluated the efficiency of urban public transport system from a macro-level perspective and propose that the efficiency of transport systems with rail is higher than that of transport systems without rail.

Most of the studies found in the presently available literature focus only on one infrastructure type such as road or rail. The network impact on the introduction of road and rail in a transport corridor is ignored, especially in developing cities. This study presents the analytical framework to investigate this impact from three standpoints, including efficiency, environment and equity. All indicators are estimated by transport network based simulations. In the above mentioned literature, Peng (2007) considers simultaneously bus networks and rail networks when evaluating the rail network. Bhandari et al. (2008) and Han and Hayashi (2008) did not consider transport networks. The rest of the studies only consider either road networks or rail networks. Here the transport network is composed of the road
network, bus network and rail network. In the simulation process, the road network is handled as the carrier of the bus network, and the bus network is regarded as the feeder system to the rail network. Thus, the connections among these three networks are established.

The above referred studies only consider passenger demand. In addition to private car traffic, the road network accommodates dominant public bus traffic and freight truck traffic. Hence, in addition to passenger demand, freight demand is also considered in this study. A case study of Dalian city, China is presented to show the complexity of a trade-off between road and rail. Four representative scenarios including do-nothing, both introduction of road and rail, introduction of only road and the introduction of only rail for the same transport corridor are analyzed respectively. The comparisons for each indicator among different scenarios are illustrated. The findings for this case study provide implications for decision makings in other developing cities.

The rest of this paper is organized as follows: Section 2 presents the analytical framework, and a detailed description of each component in this framework is explained in its subsections. Section 3 elaborates the case study for the city of Dalian, China and the analysis results are discussed. The paper ends with conclusions and final remarks in Section 4.

2. ANALYTICAL FRAMEWORK

In order to discuss the trade-offs between the introduction of road and rail infrastructure for the developing cities, an analytical framework is proposed in this study and shown in Figure 1. In the following sections the analytical framework will be described in detail.

2.1 Scenario Definition

A transport corridor is generally a linear geographic band in a specified region, which accommodates the main travel demand and plays a dominant role in the transport network. It is a trade-off decision for new transportation infrastructure such as road or rail to be introduced to such transport corridors. In this study, the parameters for design and development of road and rail are assumed suitably. New Road and new rail are almost parallel to each other from the spatial layout perspective. For new road, the lane number, design capacity, the design running speed and so on are taken as exogenous variables. For new rail, the station locations, departure frequency and the operating speed, etc., are also already known. The trade-off decision involves four cases, neither to be introduced, both to be introduced, only road to be introduced and only rail to be introduced. This study aims to examine the impact of these cases on the transport network for developing cities. Therefore, as shown in Figure 1, four scenarios corresponding to each potential case are defined here respectively. Other elements including existing transport infrastructure, passenger demand, freight demand, and so on are uniform among different scenarios.

2.2 Network-based Simulation

In order to define the evaluation indicators, a network-based simulation method is conducted for four scenarios, respectively. In the proposed simulation method the travel demand is loaded on
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The transport network. It is designed with consideration to the particular characteristics of transport systems in developing cities. It is described in the following sections.

(Figure 1) Analytical framework
2.2.1 Transport network configuration

Since the transport network is the core component of the proposed method, its configuration is presented first. Since the trips shifting between car mode and bus or rail mode rarely happens in the developing cities, the transfers between road links and transit links is ignored. Thus, integrated super transport network is not adopted in this study. The entire transport network used here is composed of two individual networks in GIS: road network and transit network. Figure 2 shows the configuration of road network and transit network in GIS. The road network is composed of a set of links representing roadways, denoted by the polyline object, and a set of nodes representing road intersections, denoted by the point object. The transit network includes the bus system and the rail system. The bus system is generally regarded as the feeder system to the rail system, especially for developing cities, and it is necessary to integrate bus systems with rail systems together. The bus system is composed of bus stops denoted by the point objects, and bus routes are denoted by the polyline objects in GIS. The rail system is comprised of rail stations denoted by the point objects, and the rail line sections denoted by the polyline objects. The platforms are also included and denoted by the polygon object in GIS. The transfer platform is the important component in the transit network since the generations of the boarding links, the alighting links and the transfer links all depend on the platforms.

Although the road network and the transit network are considered in this study, it does not mean that they are independent of each other. As the regular buses depend on the roadways, the
travel time on any bus route is influenced by its attached links on the road network. Therefore, the connection is created between road links and bus route links. Because road links are represented by the polyline object in GIS, roadways are generated by creating the buffer area along the road link. The bus route link is drawn parallel to the central line of its roadway. Therefore, it can be identified in GIS as that which links overlap the specified bus route link. As shown in Figure 2, a bus route link is represented by the purple polyline in GIS and is connected with two bus stops represented by the blue crosses. Travel time on the bus route link is subject to the travel time on the overlapping road links. The relationship is recorded in the table corresponding to bus route links and includes IDs of all overlapping road links and their overlapping length. The travel time on the purple bus route link can be estimated according to the travel time on its attached road links.

2.2.2 Modal split model with spill-over effect

This study considers passenger and freight travel demand. It is assumed that the road network can accommodate not only passenger travel demand using cars but also freight travel demand using trucks, whereas the transit network only provides services for passengers. Since passenger travel demand is accommodated in the road network and the transit network, it needs to be split into the road-based mode and the transit-based mode. For developing cities, car ownership has the main impact on above modal split. It is observed that some passengers are unwilling to choose the public transport but have to give up their preferred private car because car usage is unavailable for them. However, these passengers may be regarded as future car users due to the increase of their disposable income in the future. Therefore, a modal split model with spill-over effect is considered.

In developing countries, data is generally not sufficient to support the comprehensive utility function. Therefore, the diversity of passenger characteristics is ignored in the study. The travel time and travel distance are only taken as two independent variables in the utility function denoted by the equations (1) and (2). According to the logit model denoted by the equation (3), the probability of choosing the road-based mode (car) is calculated for the specified OD pair $ij$. However, the estimated probability may be less than or greater than the car ownership level in the $i$ th TAZ. It results in the spill-over effect, which means that in some cases the probability of choosing the car is beyond the car ownership in this traffic analysis zone (TAZ) and thus spill-over passengers are forced to shift from a road network to transit network. The spill-over effect is considered by equation (4). If this probability is greater than and equal to the level of car ownership, the number of passengers choosing a road-based mode is obtained by multiplying the total passenger trip number of this OD pair by the level of car ownership. Otherwise, this value is obtained by multiplying the total passenger trip number of this OD pair by the probability estimated using equation (3). The number of passengers choosing road-based mode divided by the car occupancy rate is the car travel demand for this OD pair denoted by $D_{ij}^c$. The number of passengers choosing a transit-based mode is calculated by equation (5).
Here, $U_1, U_2$ denote the utility function choosing the road-based mode (car) and the transit-based mode (bus/rail), respectively. $V_1, V_2$ denote the deterministic portion. $\varepsilon_1, \varepsilon_2$ denote the error term. $d_1, d_2$ denote the travel distance on the road network and transit network for the specified OD pair. $t_1, t_2$ denote the travel time on the road network and transit network between the specified OD pair. $\beta_1, \beta_1, \beta_2$ represent the parameter to be estimated, respectively. $P_{1i}^\gamma$ denotes the probability of choosing the road-based mode estimated by the logit model. $\alpha_i$ is the car ownership of the $i$th traffic analysis zone. $O_1$ is the average occupancy rate of one car. $D_{1i}^\gamma, D_{2i}^\gamma$ are car trips and passenger trips by public mode between OD pair, respectively. $T_i^\gamma$ denotes the trip number of the passengers between OD pair.

2.2.3 The assignment of passenger demand, truck demand and bus demand

To define the evaluation indicators, travel demand needs to be loaded on the transport network. Peak hour travel demand is considered here, which includes passenger demand and freight demand. It is assumed here that the car traffic has a dominant impact on travel times of buses and trucks on the roadways. It means, the estimated travel speed of buses in the transit network depends on the estimated travel speed of car traffic on the links which accommodate its corresponding bus route. For the freight travel demand, trucks are generally permitted to pass on some specified road links. In such links, their travel conditions are influenced by car traffic. As shown in Figure 1, first the modal split is estimated based on the free-flow condition of the road network and transit network. Then passenger travel demand by road-based mode is converted into the car travel demand according to the given car occupancy rate. Car travel demand is assigned to the road network by the User Equilibrium traffic assignment (Sheffi, 1985) which considers the impact of traffic congestion. Average travel time, average travel speed and traffic flow are obtained after traffic assignment. While travel time on road links is updated, travel time and speed of bus links in the transit network is estimated and updated according to the associated spatial relationship of bus route links and road links described in Figure 2. Then optimal strategy transit passenger assignment (Heinz and Michael, 1989) is used to estimate the passenger flow on each bus link and rail link in the transit network. In this transit assignment method, on-board passenger congestion is ignored and the passengers by transit-based mode are generally not sensible to such congestion in developing countries. In the subsequent step, whether an equilibrium convergence condition is reached or not is checked. If not, the model will go back to the modal split step and estimate again based on the latest link characteristics. If an equilibrium condition is reached, all link characteristics are obtained in the road network and transit network.
The passenger demand has already been loaded on the road network and transit network so far.

After passenger demand is loaded on the road network and transit network, truck demand and bus demand is considered and loaded on the road network. Truck demand is assigned to the road network according to the travel time-based shortest path rule in those permitted road links. Finally truck speed and truck travel time can be obtained. For the transit network, only passenger demand is loaded. As an electricity-powered vehicle, a train is not considered due to the zero emission while operating. In the case of bus travel demand, the number of buses in each bus route can be estimated according to a fixed bus frequency in the peak hour. It is easy to estimate the bus travel time and travel speed by following the bus route layout in GIS.

2.3 Defining Evaluation Indicators

The assignment methodology on passenger travel demand, truck travel demand and bus travel demand is elaborated in the previous section. Aiming at comparing four proposed scenarios, the evaluation indicators need to be defined in the final stage of the evaluation framework shown in Figure 1. The results obtained by the network-based simulation can be further estimated to three representative indicators viz., efficiency, equity and environment.

2.3.1 Efficiency

Network efficiency has been widely used in many studies (Gutierrez, et al., 1998; Peng, 2007; Jia et al., 2007; Vitins, 2008, Nagurney and Qiang, 2007). Accessibility, mobility, and Energy efficiency can be regarded as the variants of network efficiency and are strongly related to travel time on networks. Total travel time is the basic indicator to represent the efficiency. In addition, the estimation of total travel time needs less relevant data than those of above mentioned indicators. Here total passenger travel time is taken as one indicator which can identify the efficiency of the transport network for passenger travel demand. On the other hand, total freight transporting time identifies the efficiency for freight travel demand. Such indicators can be estimated according to travel demand and travel characteristics on each link.

2.3.2 Equity

“Equity” refers to the fairness and justice of the distribution of the impacts (benefits and costs) on two or more units. This concept has become an important issue for sustainable development and has been extensively used in various studies (Yang and Meng, 2002; Antunes, et al., 2003; Bhandari et al., 2008; Santos et al., 2008; Leck, et al., 2008). Many studies generally consider social equity related to transportation issues (Bhandari et al., 2008). However, from a network level perspective, generally the equilibrium origin-destination travel time for some OD pairs may be increased after the introduction of new transport infrastructure, leading to positive or negative results for network users. Yang and Meng (2002) examine this phenomenon. Therefore, the equity issue about the gained benefit is raised in terms of the introduction of new infrastructure.

The Gini Coefficient or Gini Index, one of the most widely used measures of inequality, can be defined as a measure of dispersion scaled by twice the value of the mean. In practice, it measures the relative difference between what we have and what would be a perfect situation.
According to the Gini Coefficient, the equation (6) is proposed to identify the equity of the benefit distribution of travel time for all OD pairs in the transport network, for passenger travel demand. The value of the coefficient \( EQ \) belongs to the interval \([0, 1]\), and the higher the value, the closer it is to the perfect situation.

The benefit \( ET_i \) is defined for a specified TAZ \( i \). After the introduction of new transportation infrastructure to the transport network, passengers travel time is decreased in some OD pairs from TAZ \( i \) to all other TAZs. Total decreased travel time for the passengers is estimated by equation (9). However, passengers’ travel time may be increased in some OD pairs from TAZ \( i \) to all other TAZs. Total increased travel time for the passengers is estimated by equation (8). After \( WT_i \) and \( BT_i \) are obtained, the equation (7) estimates that the proportion of total saving time to total changed time, denoted by \( ET_i \). And it can represent the level of benefit for a specified TAZ \( i \) which is the number between 0 and 1 for any TAZ. The higher the value, the greater the benefit. \( ET_i \) is the level of benefit for one TAZ \( i \), and this indicator should be different from TAZ to TAZ. The equity among all the TAZs is estimated by equation (6).

\[
EQ = 1 - \frac{1}{(2n^2ET)} \sum_{j \in TAZ} \sum_{k \in TAZ} |ET_j - ET_k| \tag{6}
\]

\[
ET_i = \frac{BT_i}{(BT_i + WT_i)} \tag{7}
\]

\[
WT_i = \sum_{j \in W^R} q^R_{ij} (t^R_{ij} - \overline{t^R_{ij}}) + \sum_{j \in W^T} q^T_{ij} (t^T_{ij} - \overline{t^T_{ij}}) \text{ if } \{W^R | t^R_{ij} - \overline{t^R_{ij}} > 0 \}, \{W^T | t^T_{ij} - \overline{t^T_{ij}} > 0 \} \tag{8}
\]

\[
BT_i = \sum_{j \in B^R} q^R_{ij} (t^R_{ij} - \overline{t^R_{ij}}) + \sum_{j \in B^T} q^T_{ij} (t^T_{ij} - \overline{t^T_{ij}}) \text{ if } \{B^R | t^R_{ij} - \overline{t^R_{ij}} < 0 \}, \{B^T | t^T_{ij} - \overline{t^T_{ij}} < 0 \} \tag{9}
\]

Where \( n \) is the number of TAZ and \( \overline{ET} \) is the average benefit. \( ET_j, ET_k \) denote the benefit for TAZ \( j, k \) respectively. \( WT_i, BT_i \) denote total increased travel time and decreased travel time compared to the do-nothing scenario for the \( i \)th traffic analysis zone, respectively. \( W^R, W^T \) denote the set of OD pairs where travel time of the passenger is increased for road-based passengers and transit-based passengers, respectively. \( B^R, B^T \) denote the set of OD pairs where travel time is decreased for road-based passengers and transit-based passengers, respectively. \( q^R_{ij}, q^T_{ij} \) represent the number of passengers using the road network and transit network from the \( i \)th to \( j \)th traffic analysis zone, respectively. \( t^R_{ij}, t^T_{ij} \) denote travel time from the \( i \)th to \( j \)th traffic analysis zone, for a specified scenario and a do-nothing scenario, respectively.

### 2.3.3 Environment

At present, environmental issues have been paid global attention. The emissions caused by road-based traffic are the main pollution sources. Jia et al. (2007) and Keshkamat, et al. (2009) incorporate environmental indicators for their network evaluations. In this study CO2 emission is taken as an indicator to identify the impacts of the
new infrastructure on the transport network. Passenger cars, trucks and buses which are based on fossil fuels have high levels of CO₂ emissions. Compared with them, electricity-powered rail trains have no emission. Although buses have started using the CNG as fuel, such new energy still is not adequately available in most of the developing cities. Therefore, CO₂ emissions by passenger cars, trucks and buses are estimated by the equation (9). Such emission factors can be estimated by the International Vehicle Emission Model (ISSRC, 2008).

\[ EN = \sum_a (e_a x_a l_a) \]  \hspace{1cm} (9)

Here, \( e_a \) denotes city-wide emission factors of CO₂ for passenger car fleets, truck fleets and bus fleets in g/km. Such emission factors are calculated through the emission factor function where the independent variable is the vehicle running speed. \( x_a \) refers to traffic flow of vehicle-type specified on road link a. \( l_a \) refers to the length of link a in km.

### 3. CASE STUDY

#### 3.1 City of Dalian

Dalian, China is a rapidly growing city, which has been experiencing an expanding economy in recent years. Traffic congestion is becoming much worse because travel demand exceeds the supply of the transport network. The Figure 4 shows that with the rapid growth of the economy, car ownership has been increasing since 1992, especially during 2005. It can be seen that the growth rate of car ownership has accelerated in 2002 and 2005. As a result the private car share has been rising, and on the contrary the share of public transport has begun to decrease since 2004. The situation shown in Figure 3 occurs when traffic congestion results in the deterioration of the level of service of buses running on the road.
Figure 5 shows the traffic flow pattern in 1994 and 2004 in the City of Dalian. The area marked with dot lines shapes the transport corridor which serves as the dominant traffic demand. It is found that traffic congestion in 2004 is much heavier than it was in 1994. The left side in the Figure 6 shows the road network in GIS for City of Dalian. On the right side, the transit network is represented, including the stops marked by the green points and the routes marked by the red polylines. A new road (an urban expressway), 16km long, and a new rail (a parallel subway), 18km long with 15 stations, are planned in the urban main transport corridor. The new road has 4 two-way lanes and 80km/h designated speed. The new rail has a 60km/h operation speed and its departure interval is per 10 min. As shown in Figure 6, the new road represented by the green line is almost parallel to the new rail represented by the blue lines and both of them are located in the main transport corridor marked with dotted lines. The purple points represent rail stations to be invested.
3.2 Scenario Analysis

The analytical framework presented above is developed in SAGA, the free GIS platform (Conrad and Ringeler, 2004) and is programmed by C++. The results summarized in Table 1 are estimated based on the car ownership assumed to be 35%. The one peak hour demand is loaded on the transport network. Figure 7 presents a 3-D column chart to illustrate the difference among the scenarios for efficiency, environment and equity. For the environment aspect, total CO₂ emissions involving bus, truck and passenger car is lowest in scenario-1 and highest in scenario-3. The CO₂ emission for scenario-2 is between scenario-1 and scenario-3. This situation means the introduction of road is more effective than the introduction of only rail in this level of car ownership. It can be found from Table 1 that CO₂ emission by trucks is worse than the do-nothing scenario-0. In this study travel routes are limited for trucks because of their travel behavior and road permissions. That is the reason that CO₂ emission by trucks is worse than the do-nothing scenario-0. With regard to equity, scenario-3 is the best among the scenarios. Because this equity is related to travel time and the introduction of rail promotes the best equity, this demonstrates the advantage of rail infrastructures in that rail is an independent transport infrastructure and has an exclusive space to maintain its level of service. The equity in scenario-1 is better than that in scenario-2. Considering the efficiency, scenario-1 is the best among the scenarios and scenario-3 is better than scenario-2.
Table 1: Comparison of indicators among different scenarios

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Network User</th>
<th>Indicator</th>
<th>Senario-0 (do-nothing)</th>
<th>Senario-1 (both)</th>
<th>Senario-2 (road)</th>
<th>Senario-3 (rail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Network</td>
<td>Passenger</td>
<td>Total Time (Unit: h)</td>
<td>1793036.54</td>
<td>1654662.01</td>
<td>1663365.52</td>
<td>1781060.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average Time (Unit: h)</td>
<td>12.65</td>
<td>11.59</td>
<td>11.62</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Passenger Share</td>
<td>141755.52</td>
<td>142754.64</td>
<td>143135.47</td>
<td>141267.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO₂ by PC (Unit: g)</td>
<td>193131.93</td>
<td>175557.63</td>
<td>177198.18</td>
<td>192338.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PC Average CO₂ (Unit: g)</td>
<td>1.63</td>
<td>1.48</td>
<td>1.49</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>Freight</td>
<td>Freight Total Time (Unit: h)</td>
<td>710763.75</td>
<td>654513.22</td>
<td>655816.95</td>
<td>711508.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Freight Average Time (Unit: h)</td>
<td>15.73</td>
<td>14.49</td>
<td>14.52</td>
<td>15.75</td>
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<td></td>
<td></td>
<td>Truck Total Time (Unit: h)</td>
<td>270991.50</td>
<td>251158.94</td>
<td>251641.04</td>
<td>271293.55</td>
</tr>
<tr>
<td>Trans. Network</td>
<td>Passenger</td>
<td>Total Time (Unit: h)</td>
<td>8150210.94</td>
<td>7573647.05</td>
<td>7931592.97</td>
<td>7791428.06</td>
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<tr>
<td></td>
<td></td>
<td>Average Time (Unit: h)</td>
<td>24.85</td>
<td>23.16</td>
<td>24.28</td>
<td>23.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Passenger Share</td>
<td>327994.93</td>
<td>326995.81</td>
<td>326614.98</td>
<td>328482.81</td>
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<td></td>
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<td>CO₂ by Bus (Unit: g)</td>
<td>16350.69</td>
<td>15097.90</td>
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<td>16275.87</td>
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<td></td>
<td></td>
<td>Bus Average CO₂ (Unit: g)</td>
<td>4.57</td>
<td>4.22</td>
<td>4.23</td>
<td>4.55</td>
</tr>
<tr>
<td></td>
<td>Equity</td>
<td></td>
<td>1</td>
<td>0.94</td>
<td>0.91</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Efficiency - Total Passenger Time (Unit: hour)

<table>
<thead>
<tr>
<th></th>
<th>Senario-0 (do-nothing)</th>
<th>Senario-1 (both)</th>
<th>Senario-2 (road)</th>
<th>Senario-3 (rail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment - Total CO₂ Emission (Unit: g)</td>
<td>270202.97</td>
<td>246932.05</td>
<td>248724.38</td>
<td>269402.38</td>
</tr>
</tbody>
</table>

Equity
Figure 7) Comparison among efficiency, environment and equity

Figure 8) Relationship between efficiency and car ownership
In the following analysis, a set of experiments are conducted. The first experiment keeps other factors fixed and changes the car ownership from 15% to 85%. The second experiment keeps other factors fixed and changes the passenger travel demand to double the original demand. For the do-nothing scenario, efficiency, environment and equity are assumed to be 1. For other three scenarios, the proportions of their indicators to corresponding indicators of the do nothing scenario are plotted in Figures 8 - 15 below.
Figures 8, 9, 10 and 11 show the trends of the efficiency indicator over car ownership or passenger demand for three scenarios. The lower the value, the higher the efficiency. Figures 8 and 9 are the efficiency for passengers, and Figures 10 and 11 are the efficiency for freights. It can be observed that for the efficiency, Scenario-1 is always better than other scenarios in the four figures. The finding is reasonable. From Figure 8, in the case of the high level of car ownership, the introduction of road is more effective than that of rail to improve the efficiency of the transport network. It is easy to understand that high car ownership results in high car travel demand, and the traffic congestion is more serious than before. The introduction of new road can effectively relieve traffic congestion to some extent. In Figure 9, it can be surmised that for high passenger demand rail is a better option than road, and for low passenger demand, road is an effective option. Since car ownership is not changed, the increase of total passenger demand mainly leads to the increase of transit-based passenger demand. Therefore, the introduction of the rail improves levels of service of the transit network. In Figure 10 at a low car ownership level of less than 0.4, and in Figure 11 at low passenger demand level of less than 1.4, the curve of road Scenario-2 is almost overlapped with that of Scenario-1. However, Scenario-3 has almost no improvement for the efficiency of the freight. It means that at least for the efficiency of freight demand, the introduction of only road has the same effect with both introduction of road and rail at this condition. The introduction of rail does not improve the conditions of the road system obviously, so the travel time on the links trucks choose is almost not changed. For freight demand, the situation is different as car ownership increases from 0.4. Induced traffic demand caused by the introduction of new roads will increase travel time on some main roads on which the trucks generally run. Travel time for the freight will increase. At this time, the introduction of rail attracts some passengers shifting from road to transit, and it results in the decrease of travel time on some main links truck traffic usually chooses. Therefore, the efficiency for freight is improved at high car travel demand.
The trend of equity among different scenarios, with regard to passenger demand, is shown in Figures 12 and 13. The higher the value, the higher the equity. Figure 12 identifies the relationship between equity and car ownership. For low car ownership the introduction of rail is more effective than road to improve the equity level. However, for high car ownership the introduction of road is more effective than rail. Figure 13 identifies the relationship between equity and passenger demand. Different from the efficiency, both introduction of road and rail is not the best choice for the equity. As shown in Figures 12 and 13, the equity generally prefers the...
introduction of only rail. Because the proposed equity issue is raised by the traffic congestion, the rail as an exclusive infrastructure shows its merits at this point. However, at high car ownership level in Figure 12, the equity in Scenario 2 is higher than the other two scenarios. The reason is that road traffic congestion caused by heavy car travel demand is serious enough to decrease the level of service of bus traffic. The merit of rail infrastructures is limited by its feeder system, the bus service, especially for developing cities without a dominant rail network system.

(Figure 14) Relationship between environment and car ownership

(Figure 15) Relationship between environment and passenger demand
The relationship of the environment and car ownership and passenger demand is shown in Figures 14 and Figure 15. The lower the value, the better it is for the environment. The environment indicator represents CO₂ running emission caused by cars, buses and trucks. Based on figure 14 it can be concluded that at the high level of car ownership, the introduction of only road can more effectively reduce CO₂ emissions than the rail. The reason is that road system accommodates the cars and buses demand. The bus system accommodates the most passengers by the transit-based mode and contributes more CO₂ emissions. The introduction of road can reduce the CO₂ emissions by cars and buses. At the same time the rail plays important role in the high passenger demand scenario. However, passenger demand used in Figure 14 corresponds to the demand at 1 in the horizontal axis of Figure 15. It is seen from the results that current demand is not heavy for the rail or for the capacity of the transport network. Figure 15 illustrates the relationship between the environment and passenger demand. In case of the low demand the introduction of the only rail cannot obviously reduce CO₂ emissions. In the network without congestion or with light traffic congestion, the rail cannot play its speed merit. However, at high passenger demand, the rail plays the main role to reduce the CO₂ emissions.

It can be seen from the above figures that the indicators fluctuated over car ownership or passenger demand among different scenarios. It seems to be strange but actually it makes sense. There are three points that contribute to these phenomena. The first point is the consideration of modal split with spill-over effect. The probabilities to choose the road-based mode or the transit-based mode, estimated by the logit model, are different over all OD pairs but fixed at a specified car ownership. As car ownership changes, the spill-over effect denoted by equation (4) plays its role so that such probabilities will change over all OD pairs. It provides a dynamic factor to results. The second reason is that a connection between road network and bus network is built to consider that the level of service of the bus system is also dependent on the level of service of the road system. It contributes a second dynamic factor to split the passenger demand between the road network and the transit network. The third point is that the indicator is evaluated and analyzed in a spatial network manner. A network-based simulation is a complex system where the relationship among the components or variables is not linear, but nonlinear. It demonstrates the trade-offs between road and rail is a difficult decision, especially from a network perspective.

4. CONCLUSIONS AND FINAL REMARKS

The paper presents the analytical framework to investigate the impact of the introduction of road and rail on the transport network for developing cities. A case study is conducted here to demonstrate the complexity of the trade-offs on the introduction of road or rail. The findings show that the introduction of both, the road and the rail, is the best decision to enhance the transport efficiency. The introduction of road contributes more to improve the efficiency at a high level of car ownership, but the introduction of rail contributes more to improve the efficiency at a high passenger demand. For the equity, the introduction of rail can play an important role in improving the equity level for all network users. For the environment, the introduction of road has a significant effect on reducing CO₂ emissions in
terms of cars, buses, and trucks. For developing cities, an extensive bus system is necessary to accommodate the passenger demand and control the emission pollution. Since developing cities cannot afford a dominant rail system covering the network, the introduction of rail can only reduce CO\textsubscript{2} running emissions by attracting the passengers shifting from cars to transit mode under serious traffic congestion. The decision differs from city to city, and also differs among the different development stage for the same city. The analytical framework proposed in this paper can be regarded as an effective assistant tool to judge the impact of the introduction between road and rail on environment, equity and efficiency.

In this study, the peak hour demand is loaded on different scenarios. The short-term evaluation of these indicators can be extended in the following research. The findings demonstrate that the different demand or different levels of car ownership results differently with three indicators. This point has significant implications especially for developing cities. In addition, it is necessary to consider the long-term evaluation of the impact of the transport network in order to build a sustainable transport system. In the long-term evaluation land use will change according to the introduction of new infrastructure. For instance, the introduction of rail could shape land use patterns in a compact way to achieve a sustainable development. On the other side, the introduction of road will shape residential land use so that social maintenance costs will be further raised, which may not be an apt option to sustainable development.

REFERENCES


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