# ASSESSMENT OF ROAD NETWORK PERFORMANCE WITH THE CONCEPT OF FUNCTIONAL HIERARCHY

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## ABSTRACT

A concept of the functionally hierarchical road network has been recognized since long ago, with the purpose of higher network efficiency. In order to realize that concept, junction types among individual road levels are quite important, since they determine the connectivity of roads and give a significant impact for delay. In Japan, incomplete consideration on that causes some problems such as large delay on arterial roads and passing-through traffic on local roads. For that, the impact of junctions on traffic flows needs to be assessed with the concept of functional hierarchy at the road planning stage. However, how much the network performance is affected by implementing appropriate junction types has not been quantitatively demonstrated in existing studies. Therefore, this study aims to assess the functionally hierarchical network considering the impact of junctions. The network is assessed from two viewpoints: the performance of individual road levels and the performance of an entire network, by using several indices such as travel speed and the use rate by through traffic on individual road levels. Since the existing methodologies cannot implicitly deal with the impacts of converting junction types to the travel speeds under the interaction with users' route choice, an original user equilibrium assignment which can take junction delay by type into account is proposed. By applying it, a case study with hypothetical grid network showed that replacement of key signalized intersections between highest-level roads with overpasses is quite significant to form functional hierarchy and further improve the performance of the entire network. Additionally, it is also verified that junction treatment is more effective to improve mobility than enhancing link free-flow speed under the network with dense signalized intersections.

*Keywords: functionally hierarchical road network, junction types, delay, quality of service, user equilibrium*

# INTRODUCTION

A traditional concept of functionally hierarchical road network has been proposed since long ago in the field of highway planning, with the purpose of higher network efficiency. Functionally hierarchical network classifies roads into several levels according to the priority given for mobility or access. Specifically, higher-level roads, e.g., freeways or major arterials, are operated in higher travel speed with fewer accesses to lower-level roads and/or roadside facilities. On the other hand, lower-level roads like local roads are operated in low travel speed instead of free accesses from roadsides. Between them, mid-level roads, e.g., collector-distributors, are necessary to connect the higher- and lower-level roads. This classification segregates different travel movements, namely land-access or passing-through, into corresponding roads. As a result, proper services of each road can be effectively provided: high mobility on high-level roads; sufficient access opportunity and calm traffic on low-level roads.

In order to realize this concept, several countries such as the U.S. and Germany have emphasized the importance of connectivity and junction types among individual road levels. The road planning guidelines in the U.S. (AASHTO, 2011) or Germany (FGSV, 2008) clearly describe a gradual change in road levels accommodating with users' trip stages. Furthermore, RASt (2006) provides the scheme of junction types for maintaining the functional hierarchy. Access management manual (2003) also describes the impact of junction treatments, e.g., reduction of signalized intersection density or replacement of grade intersections with overpasses, for the same purpose.

On the other hand in Japan, although there is a kind of road classification, individual road levels had been designed based on their link capacity only (Japan Road Association, 2004), and consideration on connectivity and junction types among them are quite incomplete. As a result, signalized intersections are likely to be densely placed even on major corridors. These corridors are occasionally directly connected to local roads, and then vehicles are forced to frequently stop. This also results in passing-through traffic flowing into local roads particularly when traffic calming devices are not properly implemented on these minor streets, since travel speed on major corridors is not so high. It has been considered that such problems significantly affect the network performance (Nakamura et al. (2005), Shimokawa et al. (2012), etc.). Therefore, the impact of junctions must be carefully assessed at the road planning stage.

However, those have not been quantitatively demonstrated in existing studies. In other words, it is still not clarified how much the network performance can be improved by implementing appropriate junction types. Moreover, assessment frameworks of the functionally hierarchical network has not been thoroughly developed yet, since traditional evaluation with a single typical index such as total travel time cannot directly measure the quality of service which is achieved by introducing the concept of the functional hierarchy.

Therefore, this study aims at assessing the functionally hierarchical network considering the impact of junctions. For this purpose, indices which can assess the functional hierarchy are discussed and proposed.

This paper starts with introduction and literature review followed by the explanation of special viewpoints for the functionally hierarchical network assessment in this study. After that, an algorithm of user equilibrium assignment which considers junction delay is introduced. Then, a case study with hypothetical grid network is conducted to show the impact of altering either junction types or free-flow speeds. Finally, this paper ends up with conclusions and future works.

# LITERATURE REVIEW

Basically, functional hierarchy of network which provide proper service on each road level can be interpreted by travel speed differences among individual road levels. Some of the existing guidelines like AASHTO (2011) or FGSV (2008) set target travel speeds (which are interpreted by target LOS in U.S.'s case) of different road levels for that purpose. Thus, discussions are likely to be related to either how to design network under given classification of target travel speeds or how to design each road segment to meet them.

The first point of the discussions tends to focus on optimization of hierarchical road allocation under flow-independent condition with given travel speed by level as Bigotte, J. F. et al. (2010) and Miyagawa, M. (2011) did. In contrast, Kuwahara et al. (2011) investigated the sensitivity of given travel speeds on the average travel time in the hierarchical grid network to get insight of target value settings. In these studies, given travel speed must be guaranteed at every level, which is the subject of the second discussion.

On the other hand, the second point is generally related to the manuals such as HCM (2010) or HBS (2001), which estimate travel speed of a road segment or facility under assumed traffic flow. Here, junctions are the most significant for travel speed by delay in the case of interrupted flow. However, network-based evaluation which includes the change of demand when converting junction types is beyond its objective, since existing manuals only deal with a single segment or facility.

In general, both of the above discussions cannot deal with how different junction types, which determines priority and delay for each crossing road, contribute to form the functional hierarchy in the network. As a unique study that aims to evaluate junction types in the hierarchical network, Vitins et al. (2012) compared the total costs of networks which were developed under different rules of junctions how individual road levels may be connected, considering the demand-based investment by using a meta-heuristic approach. However, their focus is rather on the network evolution, than the direct impacts on the network performance such as travel speed and travel time. Zhang, H. and Li, Z. (2011) focused on the connectivity of roads and evaluate the hierarchical structure of network by it, but that evaluation does not aimed to assess the performance of roads and network as well.

This research focuses on how the conversion of junction types affects the functional hierarchy of the network; differences of travel speeds among individual road levels and segregation of travel movements. In order to evaluate those, interaction of travel speeds with users' route choice must be considered. While this interaction is generally modelled by either static assignment or dynamic simulation, this study adopts the former, since it requires much fewer input variables which are easier to be obtained even at planning stage. However, the impacts of junctions cannot be implicitly dealt by current standard user equilibrium (UE) algorithms. Accordingly, this study proposes an original UE assignment which can take junction delay by type into account.

# VIEWPOINT OF THE ASSESSMENT

Generally, this study assesses the functionally hierarchical network by using several indices obtained through traffic assignment. In this section, two viewpoints of the assessment considering the main objective of functionally hierarchical network and corresponding indices are explained.

## The performance of individual road levels

In order to investigate effectiveness of each measure for forming functional hierarchy in the network, this study firstly assesses the performance of individual road levels by using the two indices as follows:

Travel speed is a fundamental index of the performance of individual road levels. In the functionally hierarchical network, travel speed is required to be higher for mobility on higher road levels; and that should be obviously lower in the lowest road level, which contributes to ease of access from roadside facilities and traffic calming. Thus, there must be clear differences in travel speeds among different road levels. Average travel speed of all roads belonging to each level is used to see such a general tendency. For examining more detailed conditions with local speed reduction, link travel speed distribution is used.

In addition, especially for lowest road levels, eliminating passing-through traffic is quite important for accessing traffic and also other non-motorized users such as pedestrian and cyclists. In order to verify those, the use rate by the through traffic with the same trip length is defined by road level. The use rate of level-$n$ is the percentage of the distance of level-$n$ roads travelled by all the through traffic with a certain trip length to the total distance travelled of them. This value must be small on lower road levels. Here, since route traffic volumes is not available through the deterministic methodology explained in the following chapter, it is assumed that travel demand is equally assigned to all the shortest paths.

## The performance of an entire network

Regardless of functional hierarchy, the performance of an entire network can be measured in terms of the service which users can actually receive throughout their trip. It may not be necessarily better in the case of the network with functional hierarchy than that without. Litman (2012) remarked on the increase of travel distance to channel traffic flows to higher-level roads. Investigating to which extent functional hierarchy can be advantageous is also one of the interests in this study.

Total travel time, which is the sum of travel times by all users, is often used for this purpose. However, only evaluating this single index might not be appropriate for the functionally hierarchical network, because it intends to provide high mobility for long-distance trips. However simultaneously, this incurs detours due to access control for some local short-distance trips.

For that reason, this study uses average travel speed throughout trip defined as trip travel speed hereafter, to measure the performance of an entire network for users' perspective. This index is calculated by dividing trip length, i.e., the distance between origin and destination of each trip by its travel time. Note that the impact of detour is reflected only in travel time, since trip length is defined regardless of the travelled path. This makes it possible to directly compare trip travel speeds between scenarios, even when travelled path has changed by converting junction types.

# METHODOLOGY

This chapter describes a methodology to obtain the UE flow pattern, from which the assessment indices are derived. As it has been mentioned, this methodology is based on a statistic UE traffic assignment, so as to easily be applied at road planning stage. Herein, the impacts of junctions must be reasonably contained, considering the significance of them for the operational performance of network and users' route choice behavior. However, since this study aims at assessing whether the network can provide proper services on different road levels based on the purpose of functional hierarchy, the case with extreme oversaturation at any junction with queue spillback is not dealt with as the subject.

## Link performance function

In order to address the UE algorithm, the link performance function is firstly defined. Let nodes represent junctions and a link represent a length of road between two nodes with one direction. Consider link $ij$ connecting from node $i$ to node $j$, as shown in Figure 1.

In the classic UE algorithm, typical link performance functions such as BPR function give the travel time from $i$ to $j$ as a function of only the flow of subjective link $ij$. However, such functions ignore the interdependence between opposite flow and crossing flows, as also illustrated in Figure 1. Whenever evaluating junction types, change in impacts of these conflicting flows on delay cannot be represented in that case.

To overcome that limitation, this study proposes the link performance function to define link travel time as the sum of travel time along a link by free-flow speed and junction delay incurred at the end node, as interpreted in Equation (1).

$$t_{ij}(\mathbf{x}_j) = \frac{l_{ij}}{v_{f,ij}} + d_{ij}(\mathbf{x}_j) \tag{1}$$

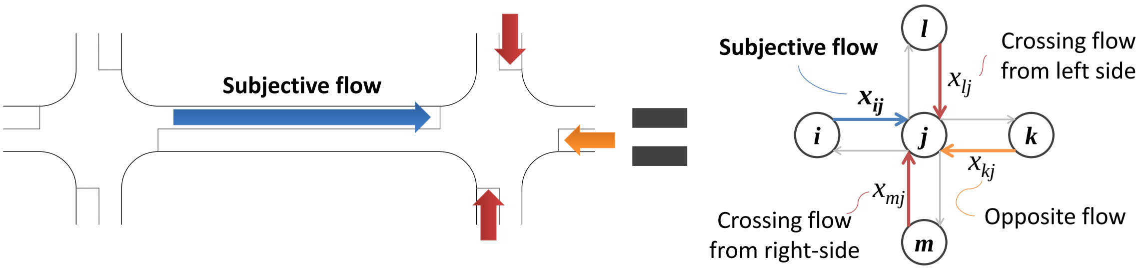
Where, $t_{ij}$: travel time from node $i$ to node $j$

$l_{ij}$: length of link $ij$

$v_{f,ij}$: free-flow speed of link $ij$

$d_{ij}(\mathbf{x}_j)$: junction delay incurred by traffic flow heading towards node $j$

$\mathbf{x}_j$: vector consisting of traffic flows inflowing node $j$, $\mathbf{x}_j = (x_{ij}, x_{kj}, x_{lj}, x_{mj})$ in the case of Figure 1.



*(in the case of left-hand traffic)*
Figure 1 Description of link *ij* and traffic flows related to travel time $t_{ij}$

## *Travel time along a link*

Travel time along the link *ij* is assumed to be flow-independent. This is because link delay with the increase of flow can be negligible in interrupted flow, due to capacity constraint at the downstream intersection, as shown in Figure 2.
Therefore, it depends on free-flow speed only in a given network configuration. Free-flow speed is determined by road level to represent its geometrical characteristic.
Link delay caused by access traffic from roadside facilities, on-street parking, and the impact of traffic calming devices are indirectly included in free-flow speed so as to simplify this methodology; the free-flow speed with these delay is preliminary reduced from the identical case, as illustrated by the shift of flow-speed curve in Figure 2.

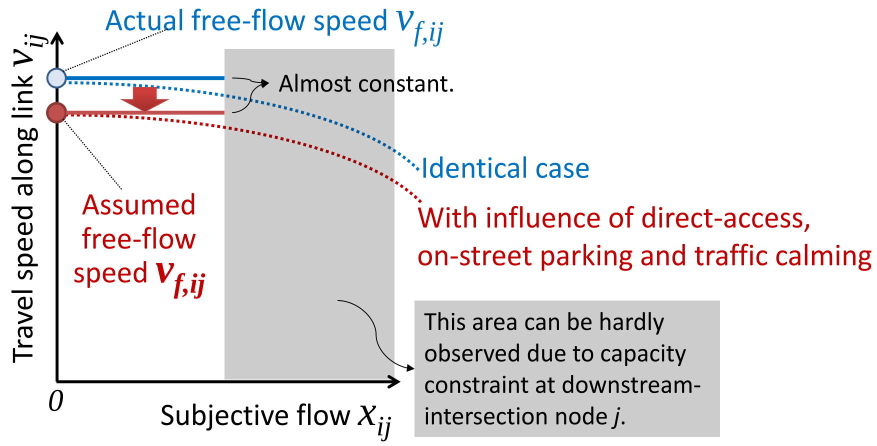
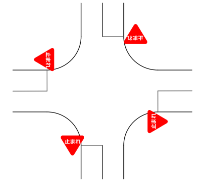
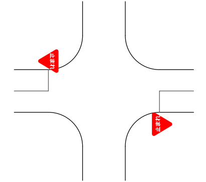
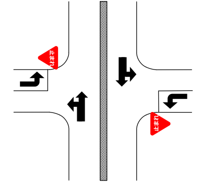
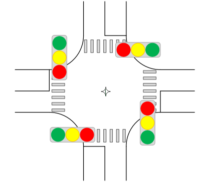
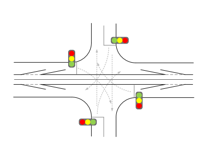
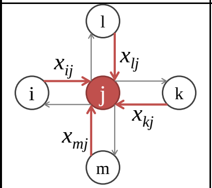
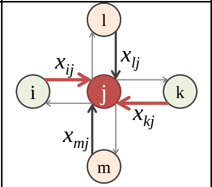
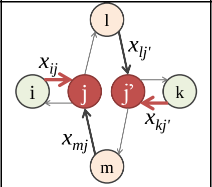
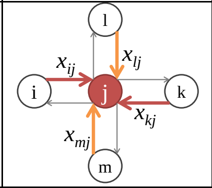
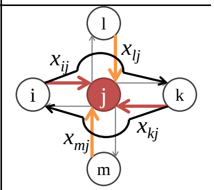
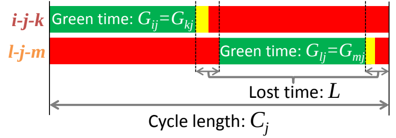


Figure 2 Flow-speed relationship of link *ij*

## *Junction delay*

Junctions are the key elements to differentiate the performance of connecting road levels for functional hierarchy. Therefore, different types of junctions must give corresponding priority of connecting roads and delay.
Five junction types in Table 1 are considered in this study. Delay is calculated by different functions as described in the following subsections:

Table 1 Junction types

| Types | | AWSC | TWSC | TWSC with median | Signalized intersection | Diamond interchange |
|---|---|---|---|---|---|---|
| Schematic illustration | |  |  |  |  |  |
| Description in traffic assignment | |  |  |  |  |  |
| Signal phasing | | | | |  | |
| Proper level | minor road | local | local | local | collector | collector /arterial |
| | major road | | collector | arterial | collector /arterial | arterial |

*(in the case of left-hand traffic)*

1. <u>AWSC (All-Way Stop-Controlled) intersection</u>: AWSC intersections would be applicable at the junctions where all inflowing links belong to the same and lowest road level. In such intersections, drivers must stop once and may have additional delay for other users from other directions. This study simply defines delay as fixed 3 [sec], since the impact of demand is almost negligible in lowest-level roads in many cases.

2. <u>TWSC (Two-Way Stop Controlled) intersection</u>: TWSC intersections would be effectively applied to give a clear priority for higher-level (major) roads towards lower-level (minor) roads. Delay at TWSC intersections are calculated by using the Highway Capacity Manual (2010) method, without considering the delay of turning-movements for the simplification. That means inflowing traffic from major roads does not incur any delay, while traffic from minor roads incur certain delay for gap acceptance. In this method, delay of minor traffic is a function of both the subjective flow and the capacity which is calculated by the crossing flows on major roads.

3. <u>TWSC intersection with median</u>: Physical median along higher-level roads would make a priority between two crossing roads much clearer. After installing it, an intersection is divided into two TWSC intersections with three legs, as illustrated in Table 1. Delay at each of the two TWSC intersections is calculated by applying the method mentioned above.

4. Signalized intersection: Signalized intersections are often applied to the junctions between relatively higher-level roads with heavier traffic. In this study, all signalized intersections are assumed to be isolated and controlled with a typical 2-stage phasing, as shown in Table 1, with neglecting turning delay. Delay is calculated by referring a basic concept of the HCM method, but simply the uniform delay is considered in undersaturation case, and additional delay keeps being accumulated during the analysis period in oversaturation case. Signal control parameters such as cycle length and green times are computed in the process of delay calculation, to minimize delay according to flows into the intersection.

5. Diamond interchange: Interchanges, which elevate through lanes into overpass from the at-grade signalized intersection, would be quite recommended for the junctions of higher-level roads, in order to keep mobility. This type of junctions can be represented by directly connecting node $i$ and $k$ with additional link $ik$, as illustrated in Table 1. By using this link $ik$, through movement from $i$ to $k$ gets not to incur any delay, while turning movement still cannot avoid delay at signalized intersection $j$ calculated by the above method.

## Diagonalization method for UE with asymmetric flow interaction

Since the link performance function is dependent on mixed flows from different links, asymmetric flow interaction cannot be ignored in this methodology. One of the algorithms for such asymmetric interaction is known as the diagonalization method, which is based on solving a series of "diagonalized" problems (Sheffi, Y. (1985)). The diagonalized problem is a standard UE equivalent minimization in which objective function includes simple link performance functions depending on the subjective flow only; all other flows which may affect link $ij$, namely opposite flow and crossing flows in this study, are fixed at their values during the iteration, as interpreted in Equation (2).

$$\min Z^n(\mathbf{x}) = \sum_{i\in I}\sum_{j\in J}\int_0^{x_{ij}} t_{ij}(\omega, {x_{kj}}^n, {x_{lj}}^n, {x_{mj}}^n)\,d\omega \tag{2}$$

Where, $Z_n$: the objective function at $n$th iteration

$I$ and $J$: a set of all nodes to be origins and destinations in the network

In the general process, diagonal problem is solved by using any UE minimization method (e.g., the Frank-Wolfe method) iteratively until the flow pattern becomes converged. The obtained flow pattern is proved to be an equilibrium flow pattern, at given converged cases.

## Limitations of the methodology

It should be noted that the proposed methodology has special assumptions and limitations to include junction delay into the traffic assignment implicitly. Especially, attentions must be paid to followings:

### *Parameter settings at signalized intersections*

This methodology calculates delay at signalized intersections with optimizing signal parameters during iteration. This could be regarded as operating each of all intersections by adaptive signal control, which sequentially adjusts signal parameters to the current demand. Considering the current practice where adaptive signal control is often applied, the proposed methodology would be still reasonable. However, in fact, this way cannot achieve the social optimal.

Against that, the optimization of signal parameters are often addressed as a bi-level problem (e.g., Ziyou, G. and Yifan, S. (2002), Taklu, F. et al. (2007), etc.); the optimization of signal parameters by transportation planners on the upper level, and the UE on the lower level. Besides, signalized intersections are occasionally coordinated in other cases. These discussions had better to be incorporated in the future.

### *Limitation of the diagonalization method*

Convergence through the diagonalization method is not proved with the assumed link performance function in this study, because its Jacobian is not necessarily positive definite in the case that includes delay at signalized intersections. In addition, the equilibrium flow pattern is not always unique with that problem.

Although these theoretical limitations remain as the future work, this study utilizes this diagonalization method by carefully examining the convergence condition. If the algorithm can be converged at end, it means that at least one of the equilibrium flow patterns is successfully obtained.

# SCENARIO DEVELOPMENT

Hereafter, a case study is conducted to demonstrate the impacts of junction types on the performance of functionally hierarchical network through scenario comparison. To exemplify those impacts, a hypothetical urban grid network is used. For that, several classification scenarios are developed by changing the rule of junction types and free-flow speeds. Convergence conditions of the UE assignments are also noticed at the end of this chapter.

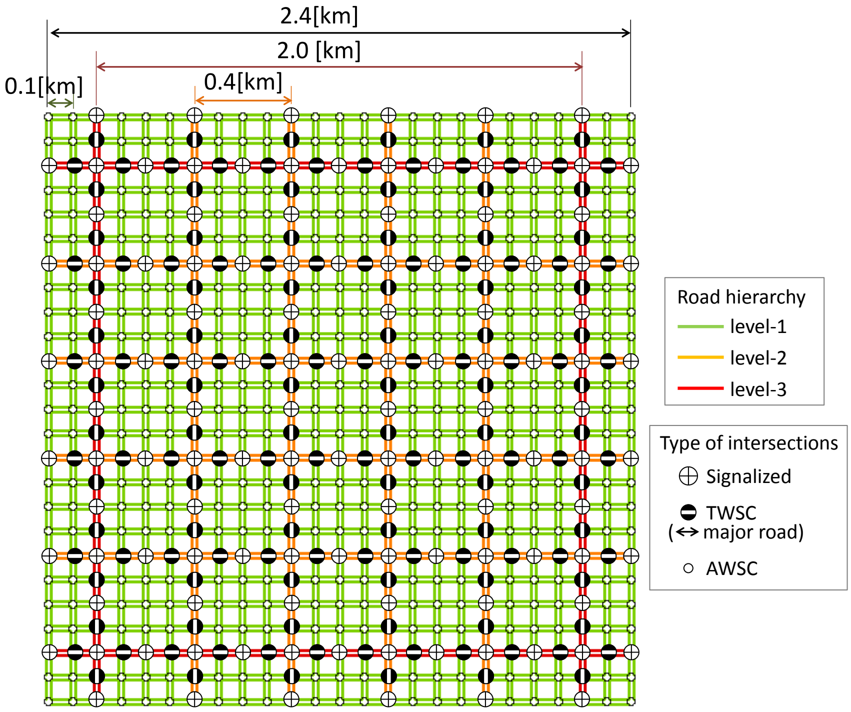
## General network configuration

A 25 × 25 grid network is adopted to represent an urban road network with simplified condition, which consists of 625 nodes and 2400 links for both directions, as illustrated in Figure 3 (a). Length of each link is 0.1 [km].

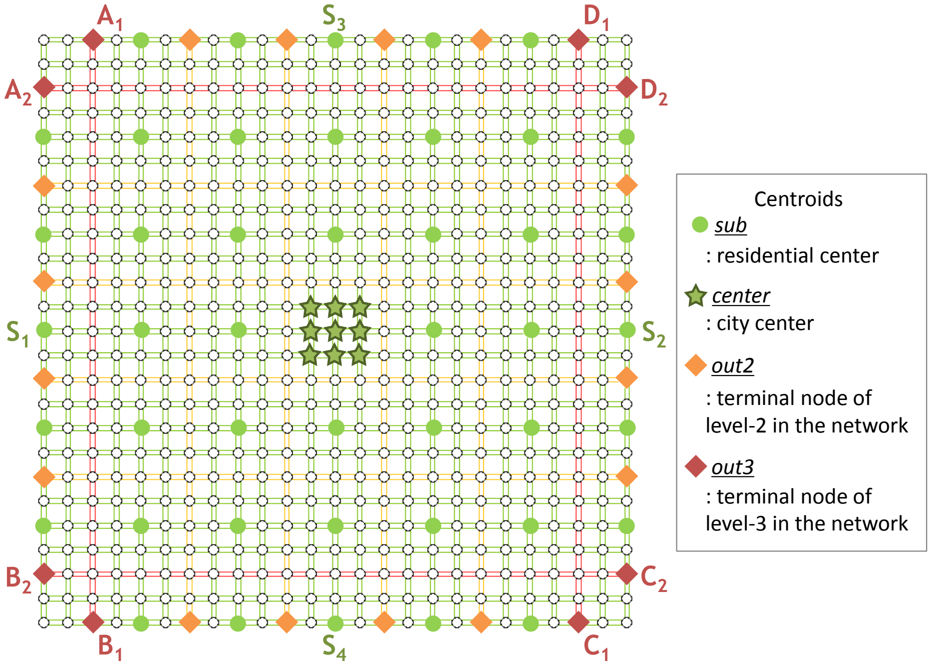
The network is classified into three levels: level-1 as the lowest for access (i.e., local roads); level-2 for the connection between level-1 and level-3 (i.e., collector/distributors); and level-3 as the highest for mobility (i.e., major arterials). Only level-3 contains multilane highways while others are two-lane. The allocation of each road level in the network is also shown in Figure 3 (a).

## Travel demand

Four types of centroids, i.e., *sub*, *center*, *out2* and *out3*, which generate and attract travel demand are symmetrically placed as shown in Figure 3 (b): *Sub* and *center* are actual centroids inside the subjective network, while *out2* and *out3* stand for the demand from/to outside the network. Thus, different types of travel demand, i.e., internal, inward/outward and through trips, are explained as the combinations of them, as defined in Table 2.



(a) Initial settings of the network: *Base scenario*



(b) Allocation of OD-centroids
Figure 3 A grid network and centroids.

Total number of trips in Table 2 is assumed by reflecting general characteristics of that in the City of Nagoya, Japan considering the balance of the trip-length distribution. Overall, there is a high proportion of inward/outward trips (about 75%), but less internal trips (less than 15%).

Table 2 Travel demand distribution

| Type of trips | Origin↔destination | Boundary condition | Number of trips per OD-pair [veh/pair] | Total number of trips [veh] |
|---|---|---|---|---|
| inner | *sub↔sub* | Trip length>1 [km] | 1 | 1656 |
| | | Trip length>2 [km] | 2 | |
| | *sub↔center* | Trip length>1 [km] | 4 | 1760 |
| inward / outward[*1] | *out2↔sub* | | 2 | 4224 |
| | *out2↔center* | | 3 | 576 |
| | *out3↔sub* | | 12 | 12672 |
| | *out3↔center* | | 18 | 1728 |
| through[*2] | *out3↔out3* | Straight[*3] | 100 | 3200 |
| | | Diagonal[*4] | 50 | |
| Total | | | | 25816 |

**1: Inward/outward trips are assumed to use either level-2 or level-3 to enter/exit the subjective network for their mobility, according to their actual trip lengths to the origin/destination outside.*

**2: All through trips are assumed to use level-3 to enter and exit the subjective network, since their trip lengths may be long enough to access level-3.*

**3: E.g.,* $A_1 \leftrightarrow B_1$, $A_2 \leftrightarrow D_2$ *in Figure 3 (b), *4: E.g.,* $\{A_1, A_2\} \leftrightarrow \{C_1, C_2\}$ *in Figure 3 (b)*

## Classification scenarios

A classification scenario determines junction types and free-flow speeds of all of the three levels. Seven scenarios are prepared for comparisons. As an initial scenario, “*Base*” scenario is assumed for the case where functional hierarchy can be hardly formed. Other five scenarios are to improve this scenario by changing either junction types or free-flow speeds for either mobility improvement or traffic calming.

### *Base scenario*

Junction type between level-*m* and level-*n* ($\text{junction}_{(m,n)}$, hereafter) of “*Base*” scenario is listed in Table 3 (a), also illustrated in Figure 3 (a). Free-flow speed is 30, 40 and 60 [km/h] for level-1, 2 and 3 respectively.

It can be recognized that this scenario has many signalized intersections, just as in the case of real network with mobility problem. Actually, the numbers of signalized intersections of level-2 and level-3 are the same. Hence, these two levels are considered to be hardly differentiated despite the difference in free-flow speed.

On the other side, level-1 is assumed to have no treatment for traffic calming, as reflected by little difference with level-2 in their free-flow speeds.

### *Measures of functional hierarchy*

All six scenarios to improve "*Base*" scenario are listed in Table 3(b). Basic policy of each scenario is either mobility improvement of level-3 or traffic calming of level-1.

The common purpose of the first three scenarios, "*JM1*", "*JM2*", and "*JM3*", is mobility improvement of level-3 by junctions: "*JM1*" converts all junctions$_{(3,1)}$ into TWSC intersections by removing traffic lights and "*JM2*" installs median along level-3 in addition to "*JM1*". "*JM3*" converts junction$_{(3,3)}$ into diamond interchanges in addition to "*JM2*". Overall, "*JM1*", "*JM2*" and "*JM3*" are the step-by-step improvement of level-3 mobility.

On the other hand, the purpose of "*C*" is traffic calming of level-1. Traffic calming is often achieved by implementing some devices such as hump or chicane, and this study considers this effect indirectly by assuming 10-km/h free-flow speed reduction, as explained in Figure 2. *"JM3+C*" is a scenario which has measures for both mobility and traffic calming for the corresponding levels to show the combined effect of them. By implementing both of the mobility and traffic calming treatments, the functional hierarchy is expected to be formed. Here, there is a hypothesis that traffic calming should be implemented with the mobility improvement in order to enhance the entire network performance. In order to verify this, "*JM3+C*" is compared with "*C*".

Furthermore, "*LM+C*" is the comparative scenario to "*JM3+C*", which also has measures for both mobility and traffic calming; however, mobility improvement is not done by junctions but links. It increases free-flow speed of level-3 without converting any junction type from *Base* scenario. By comparing "*LM+C*" and "*JM3+C*", impacts on functional hierarchy by different approaches for mobility improvement can be discussed.

Table 3 Classification scenarios

(*a*) Free-flow speeds and junction types assumed in *Base* scenario

| Minor<br>Major | Level-1 | Level-2 | Level-3 | Free-flow speed $v_f$ [km/h] |
|---|---|---|---|---|
| Level-1 | AWSC | | | **30** |
| Level-2 | TWSC and Signalized | Signalized | | 40 |
| Level-3 | **TWSC and Signalized** | Signalized | **Signalized** | **60** |

***Bold** *items are changed in the scenarios below (b)*

(*b*) Scenarios with measures of functional hierarchy

| Scenario | Mobility improvement | | | Traffic calming |
|---|---|---|---|---|
| | Junction$_{(3,1)}$ | Junction$_{(3,3)}$ | $v_{f3}$ [km/h] | $v_{f1}$ [km/h] |
| *Base* | TWSC and Signalized | Signalized | 60 | 30 |
| *JM1* | **TWSC** | | | |
| *JM2* | **TWSC with median** | | | |
| *JM3* | | **Interchange** | | |
| *C* | TWSC and Signalized | Signalized | | **20** |
| *JM3+C* | **TWSC with median** | **Interchange** | | |
| *LM+C* | TWSC and Signalized | Signalized | **70** | |

### Convergence Conditions

The UE assignment is done for all scenarios by using the proposed methodology. Iteration stops either when the change in the value of objective function becomes less than 1.0 [veh×sec] or when the number of iteration exceeds 500.

Table 4 lists up convergence conditions. For a reference, conditions of the result of a standard UE with modified BPR function for Base scenario is also listed as "*Base(BPR)*" scenario. From this table, it can be regarded that all scenarios are sufficiently converged.

Table 4 Convergence conditions of the scenarios

| Scenario | Number of iterations | Rate of change in objective function[*1] | Maximum change in link traffic flow[*2] [veh] | Rate of change in link traffic flow[*3] |
|---|---|---|---|---|
| *Base* | 432 | $1.4\times10^{-7}$ | 3.0 | 0.0016 |
| *JM1* | 309 | $5.3\times10^{-9}$ | 3.9 | 0.012 |
| *JM2* | 500 | $7.7\times10^{-4}$ | 6.0 | 0.0054 |
| *JM3* | 280 | $9.0\times10^{-8}$ | 3.1 | 0.019 |
| *C* | 263 | $1.5\times10^{-8}$ | 2.2 | 0.0016 |
| *JM3+C* | 173 | $7.9\times10^{-9}$ | 5.0 | 0.0018 |
| *LM+C* | 500 | $3.7\times10^{-4}$ | 1.4 | 0.00062 |
| *Base(BPR[*4])* | 500 | $2.1\times10^{-6}$ | 2.8 | 0.0019 |

**1: Calculated by $|Z^n - Z^{n-1}| / Z^n$, where, $Z^n$ is the objective function at nth iteration.*

**2: Maximum value of $|x_{ij}^n - x_{ij}^{n-1}|$ among any i, j.*

**3: Maximum change in link traffic flow (*2) divided by link traffic flow on that link.*

**4: For parameters of modified BPR function, $\alpha$=2.62, $\beta$=5.00 and $Cap_{ij}$=900 [veh/h] are assumed.*

## RESULTS

### The performance of individual road levels

In order to evaluate the performance of individual road levels, two indices, travel speed and the use rate of through traffic are shown in Figure 4 and Table 5. The first subsection discusses impacts of mobility improvements by junctions, from scenario "*JM1*" to "*JM3*". Secondly, the impact of traffic calming is discussed by "*C*" and "*JM3+C*". Finally, the third section compares the impacts of mobility improvement by junction types ("*JM3+C*") and that by link free-flow speed ("*LM+C*").

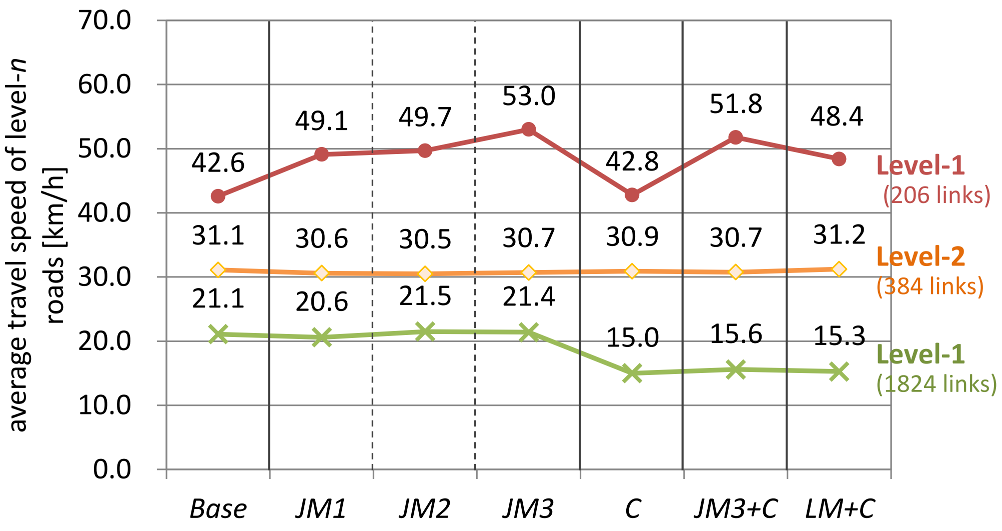


Figure 4 Average travel speed of each road level

Table 5 Use rate by road level of through trips

| Scenario | Straight through trips[%] | | | Diagonal through trips [%] | | |
|---|---|---|---|---|---|---|
| | Level-1 | Level-2 | Level-3 | Level-1 | Level-2 | Level-3 |
| *Base* | 0 | 0 | 100 | 3.4 | 0 | 96.6 |
| *JM1* | 10.7 | 7.1 | 82.1 | 4.5 | 38.6 | 56.8 |
| *JM2* | 0 | 0 | 100 | 2.3 | 0 | 97.7 |
| *JM3* | 0 | 0 | 100 | 0 | 0 | 100 |
| *C* | 4.0 | 7.4 | 88.6 | 0 | 43.2 | 56.8 |
| *JM3+C* | 0 | 0 | 100 | 1.1 | 0 | 98.9 |
| *LM+C* | 0 | 0 | 100 | 3.4 | 0 | 96.6 |

### *Impacts of mobility improvement*

In Figure 4, "*JM1*" can effectively increase the average travel speed of level-3 since it releases many links from junction delay by reducing the number of signalized intersections. However, Table 5 shows that the use rate of level-1 and level-2 increases by "*JM1*", which means the passing-through traffic on these roads cannot be prevented. This is because delay at intersections which are still signalized (i.e., junctions$_{(3,2)}$ and junctions$_{(3,3)}$) increased locally as a result of concentration of crossing flows. Although "*JM1*" seems to be effective in terms of "average" travel speed, it still failed to segregate travel movements.

Regarding "*JM1*", it is not so effective to increase the average travel speed of level-3, but meanwhile, it can work for preventing the passing-through traffic by restricting the movements of them with median.

"*JM3*" can increase the average travel speed of level-3, as well. This implies that delay at junctions$_{(3,3)}$ is quite significant for entire mobility of level-3, since it achieves great travel speed increase even though the number of signalized intersections$_{(3,3)}$ is limited to four only.

In summary, it is found that mobility of level-3 can be gradually improved by reducing traffic lights ("*JM1*"), installing median ("*JM2*") and implementing interchanges ("*JM3*"). At the same time, passing-through traffic becomes prevented from level-1 road.

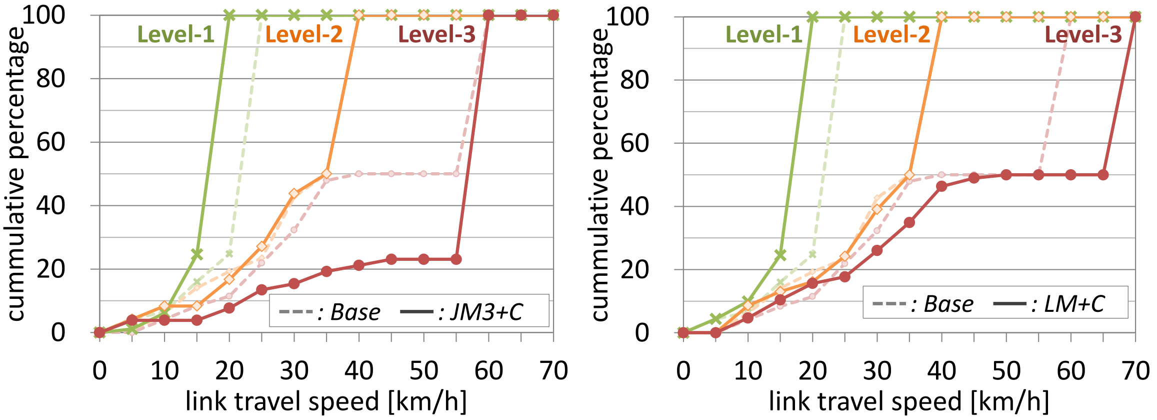
### *Impact of traffic calming*

In Figure 4, the scenario "*C*" decreases the average travel speed of level-1, and it seems to result in the clear difference between level-1 and other level roads in their functions. However, Table 5 shows that some of the through trips use level-1 and 2 in "*C*", against its purpose for preventing passing-through traffic. This happens because of the lack of mobility improvement of higher-level roads. That is, traffic flows once concentrate too much on higher-level roads because of the reduction of travel speed on level-1, then, that makes delay at signalized intersections along level-3 quite large and finally through trips change their routes to use lower-level roads. This is the typical failure of traffic calming.

In contrast, "*JM3+C*", which has both mobility improvement and traffic calming, clearly differentiates level-1, 2 and 3 in terms of travel speeds while preventing the through traffic on lower road levels. It is concluded that the functional hierarchy is successfully formed in this scenario. By comparing "*JM3+C*" to "*C*", it is also verified that mobility improvement is essential for the functional hierarchy.

### *Junction type vs. free-flow speed*

In Figure 4, "*LM+C*" can also increase the average travel speed of level-3, but not higher than in "*JM3+C*". However, as shown in Figure 5, the big difference is found when the travel speed distributions are compared in both "*JM3+C*" and "*LM+C*". Actually, Figure 5(b) shows that a half of level-3 links has almost no improvement because of delay, and which makes difference between level-2 and level-3 unclear. This result shows that just 10-km/h increase of free-flow speed is not effective in such a condition with dense signalized intersections. It proves that junction treatments are quite significant for mobility improvement.



(a) *JM3+C* against *Base*　　(b) *LM+C* against *Base*

Figure 5 Travel speed distribution

## The performance of an entire network

As a typical index of the performance of the entire network, total travel times are compared in Figure 6. It is found that “*JM3*” has the minimum total travel time; however, this comparison cannot give a whole picture of the assessment of functionally hierarchical network, since scenarios which have traffic calming treatment are never expected to reduce the total travel time. In that sense, it is necessary to assess the performance of the network by considering the impacts on individual types of trips.

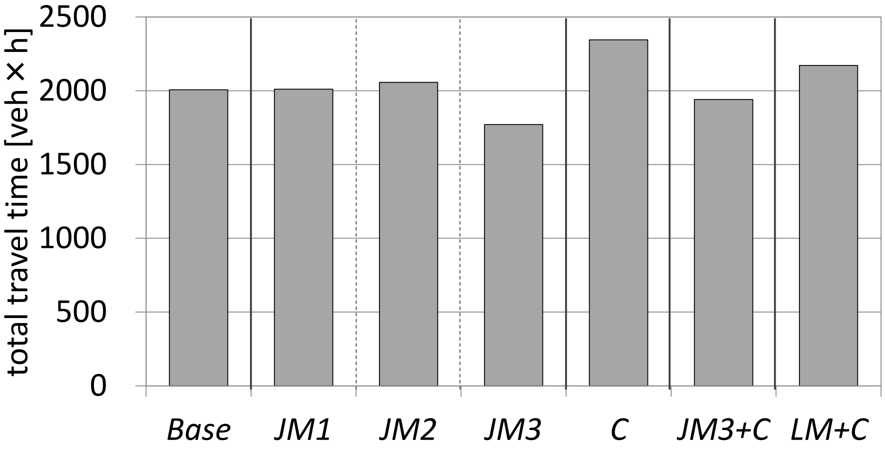


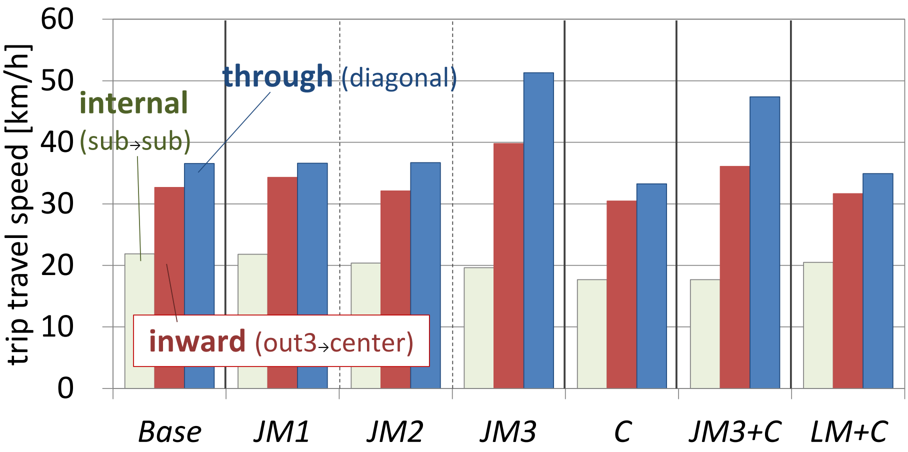
Figure 6 Total travel time

For that, Figure 7 shows trip travel speeds by type considering the difference of their actual trip lengths (a), with the increase of them from that of “*Base*” scenario (b).

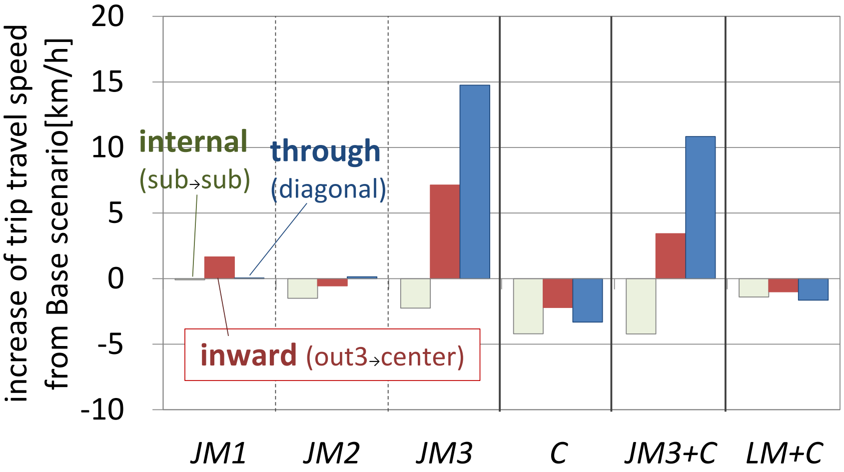
In Figure 7, actually, “*JM1*” and “*JM2*” do not effectively increase through-trip travel speed, which are targeted by these scenarios. This is because of the local large delay at junctions$_{(3,2)}$ or junctions$_{(3,3)}$, as explained in the previous section. Compared to them, “*JM3*” is found to increase through-trip travel speed quite effectively. From this result, it is verified that junctions between highest road levels are crucial to determine the mobility performance of the entire network, as well. Although there is a negative impact on internal trips for the detour on account of median (“*JM2*” and “*JM3*”), generally, increase of travel speeds is more meaningful for through trips than that for internal trips, considering their trip lengths.

It should be noted that implementing traffic calming treatment only (“*C*”) gives negative impact on any type of trips, even for through trips. However, if it is conducted with mobility improvement (“*JM3+C*”), effects on travel speeds of through and inward trips can be still positive.

Unlike “*JM3+C*”, “*LM+C*” is found to have small negative impacts on all the three types of trips. This is because of the fact that half of level-3 links do not have mobility improvement as explained in the previous section. Again, significance of junction improvement is verified from this result.



(a) Trip travel speed in each scenario



(*b*) Increase of trip travel speed from *Base* scenario

*Every travel speed is average value of representative trips;*
**Internal: Trips between "sub"s which may need the longest detour to cross two level-3 roads and pass the area of city center (i.e., $S_1$↔$S_2$, $S_3$↔$S_4$ in Figure 3(b),*
**Inward/outward: City center accessing trips, from each of "out3"s to the center of "center"s,*
**Through: Diagonal through trips (noted in Table 2) which are the longest trip length.*

Figure 7 Trip travel speed

# CONCLUSIONS

This study developed a framework to assess the functionally hierarchical network from two viewpoints: the performance of individual road levels and the performance of an entire network. By fully recognizing the importance of junctions on the formation of functional hierarchy, the static UE assignment with the link performance function which includes junction delay was proposed. Through a case study, it was verified that this methodology can reasonably evaluate the impacts of converting junction types as well as free-flow speeds.

The result of the case study with a hypothetical grid network successfully explains the formation of functional hierarchy by travel speeds and use rate by through traffic. Generally, this case study verified followings:

1. Mobility improvements can hardly be achieved by reducing the number of signalized-intersections only but its packaged measures combined with median and interchanges are important,

2. replacement of grade signalized intersections between the highest-level roads by overpass is quite significant to improve the network mobility,

3. in order to enhance the entire network performance through forming the functional hierarchy, traffic calming should be implemented together with the mobility improvement, and

4. junction treatment is more effective to improve mobility of the corridor than raising its free-flow speed particularly when signalized intersections are densely placed.

Although only junction types and free-flow speeds are the subject of the evaluation in this paper, the methodology enables to evaluate any given network with various topological shapes and classification scenarios. The impacts of spacing of each road level or the number of road levels need to be further investigated.

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