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Empirical analysis of cut-based approach for screen-line traffic counting location problem with pre-installed sensors

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Abstract Link traffic volume, which is crucial for transportation planning, requires sufficient observations while minimizing costs. When link traffic volume observations achieve screen-line coverage, all routes between OD pairs can be monitored, enabling comprehensive network traffic analysis, including OD trip matrices. The screen-line traffic counting location problem is to determine the minimum set of links that effectively separate OD pairs. This paper extends the problem to real-world road networks where some links are already observed by pre-installed sensors. We formulate an additional sensor location problem that accounts for existing infrastructure to achieve complete screen-line observation. By applying our approach to the road network of Kochi Prefecture, we provide insights into the spatial relationship between current pre-installed sensors and optimal locations for additional observation sensors.

Keywords screen-line traffic counting location problem · traffic observation · cut · additional sensor location

1 Introduction

Link traffic volumes on specific road network segments are foundational data not only for understanding current road conditions and for transportation planning but also for constructing and analyzing traffic theoretical models. In particular, to properly implement traffic model analyses, a sufficient number of link traffic volume data are required. For example, in OD trip matrix estimation models, input from a considerable number of link traffic volume measurements is necessary for high-precision estimation. Furthermore, collecting adequate link traffic volume data is vital for the proper execution of various traffic theory models. Currently, in many regions, extensive link traffic volume counts are conducted on major road segments. However, traffic observation poses substantial costs for installing and maintaining monitoring equipment. Therefore, appropriate selection of observation locations is necessary to maximize effectiveness at minimal cost.

The study of mathematically determining locations of traffic volume observation is traditionally known as the traffic sensor location problem [11]. Such research identifies the optimal locations of traffic volume observation devices ("sensors") capable of achieving observation objectives. Various such objectives have been proposed, principally including observation of link flow [7, 8] and path flow [4, 5].

This research focuses on the screen-line observation objective. Here, "screen line" refers to a set of links that separate OD pairs, namely a set of links that observe all routes between OD pairs at least once. The problem of mathematically determining the set of links that constitute screen lines in a road network was proposed by [16] as the screen-line traffic counter location problem (SLTCLP). The SLTCLP consists of two subproblems:

– Locating sensors to form a screen line considering the minimum number of sensor locations that separate all OD pairs (SLTCLP1)

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– Locating sensors to form a screen line that maximizes the number of separated OD pairs under an upper limit of available sensors (SLTCLP2)

Many path-based approaches to solving the SLTCLP have been proposed, which premise the enumeration of routes between OD pairs [10, 12]. However, the computational cost of OD route enumeration is enormous, making application to realistically large-scale road networks difficult. To address this challenge, many conventional methods have adopted heuristic solution approaches that do not necessarily achieve OD separation [6, 15]. However, these solution methods do not guarantee perfect OD separation nor necessarily solve for link sets that satisfy the original definition of screen lines. Recognizing this, we previously constructed a solution approach based on OD cuts as a method to efficiently solve the SLTCLP exactly [13]. This OD cut-based solution is advantageous as an exact solution method for the SLTCLP, making it possible to obtain solutions even in realistically large-scale road networks.

Traffic volume observations have been continuously conducted for many years, and numerous sensors have been installed on actual road networks. However, the traditional SLTCLP does not consider such pre-installed sensors. If the SLTCLP could be constructed to minimize the addition of sensor-located links given the locations of pre-installed sensors, the practical utility of this research topic for analyzing road networks equipped with numerous existing devices could be significantly improved.

Recognizing this possibility, this research extends the authors' SLTCLP1 formulation [13] to formulate a problem of additional sensor locations to achieve screen-line observation given initial sensor locations. In addition, using the proposed method, we analyze the road network of Kochi Prefecture based on the SLTCLP and its extension problem regarding link traffic volume observation location. Through this analysis, we examine the relationship between pre-installed sensor locations and additional sensor locations when screen-line observation is the goal. The main contributions of this paper are as follows:

– We extend the SLTCLP to formulate an additional sensor location problem that considers current sensor configurations.
– We use the proposed method to analyze the road network of Kochi Prefecture, providing insights into the relationship between pre-installed sensors and additional sensors under the objective of screen-line observation.

2 Abstract of cut-based formulation for SLTCLP1 proposed by the authors [13] and its extension

2.1 Abstract of cut-based formulation for SLTCLP1 proposed by the authors [13]

2.1.1 Concept of cut-based solution approach

[13] proposed a solution method for the SLTCLP based on OD cut optimization. This section outlines the formulation of SLTCLP1, which is the focus of this research. For detailed discussion, please refer to [13]. To explain the formulation shown in [13], we first present two definitions as properties of graphs related to OD separation by screen lines and OD cuts:

Definition 1. In a directed graph $G(V, E)$, an OD pair (s, t) is said to be separated if there exists no directed path between the two nodes (s, t).

Definition 2. In a directed graph $G(V, E)$, a cut C_{st} for an OD pair (s, t) is a set of links such that there exists no directed path between (s, t) in $V \setminus C_{st}$.

In particular, a cut that satisfies Definition 2 with the minimum number of links is called a minimum cut.

Given Definitions 1 and 2, the screen lines in the SLTCLP correspond to cuts between OD pairs. That is, the optimal screen lines can be considered as a set of cuts that separate all OD pairs with the minimum number of links.

2.1.2 Cut-based formulation for SLTCLP1 [13]

The mathematical problem of minimizing the number of links included in the set of links that separates all OD pairs is well known as the minimum cut problem. Based on this problem, [13] proposed a cut-based formulation for SLTCLP1. The fundamental idea is to consider the minimum cut problem independently for all OD pairs in parallel and then integrate the results. Notably, the union of the sets of links, C_{st}, which represents the optimal cuts for each OD pair, $\bigcup_{(s,t)\in W} C_{st}$, does not necessarily constitute the optimal solution to SLTCLP1, i.e., the link set that separates all OD pairs with the minimum number of links. Therefore, the optimal cut that separates all OD pairs cannot be obtained solely by determining the optimal cut for each OD pair individually. To address this, one should formulate the minimum cut problem for each OD pair in parallel, introduce variables that are shared across all these formulations, and determine the globally optimal cut through these variables common to all OD pairs.

Furthermore, the set of minimum cut problems described in parallel for each OD pair can be consoli-

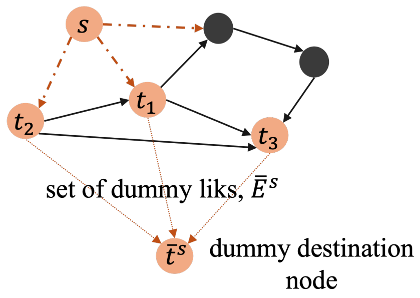


Fig. 1: An extended network for solving the minimum cut from the centroid s between other centroids $Q \setminus \{s\}$.

dated into formulations based on each centroid. Specifically, the minimum cut problem for each OD pair, $(s,t)|(s,t) \in W, s, t \in Q \subset V$, can be reduced to a minimum cut problem between each centroid $q \in Q$ and its complement $Q \setminus \{q\}$. Such centroid-based minimum cut problems can be formulated on an extended network constructed by adding dummy sink nodes and dummy links to the original network. As illustrated in Figure 1, a dummy sink node $\bar{t}^s \in \bar{V}$ is introduced to represent all the destination nodes other than the origin s, and is connected to each actual destination node via dummy links. Each dummy link is assigned a sufficiently high link cost $M(< |E|)$. In this extended network, the minimum cut that separates three OD pairs can be obtained as a minimum one-to-one cut between the origin s and the dummy sink node $\bar{t}^s$. This formulation can be justified as follows: because each dummy link has a sufficiently high cost M, it is guaranteed that these links will not be included in the minimum cut. Therefore, the minimum cut between $(s, \bar{t}^s)$ consists solely of real links, effectively separating all the destination nodes from the origin. Consequently, this minimum cut also separates each OD pair, and thus constitutes a link set that separates all OD pairs with the minimum number of links.

Based on the above discussion, the cut-based formulation of SLTCLP1 can be denoted COP1. In this formulation, for each centroid q, we consider the minimum cut problem on the extended network as illustrated in Figure 1, treating q as the origin node. Note that the extended network satisfies $\dot{E} = E + \bar{E}, \dot{V} = V + \bar{V}$.

COP1 [13]

$$\min_{k,l} \sum_{e \in \dot{E}} c_e l_e \tag{1}$$

subject to

$$-k_i^q + k_j^q - l_e \leq 0, \quad \forall q \in Q, \forall (i,j) = e \in \dot{E} \tag{2}$$

$$-k_s^q + k_t^q = 1, \quad \forall q \in Q, \forall (s,t) \in \dot{V} \tag{3}$$

$$0 \leq k_i^q \leq 1, \quad \forall q \in Q, \forall i \in \dot{V} \tag{4}$$

$$l_e \in \{0,1\}, \quad \forall e \in \dot{E} \tag{5}$$

where

$$c_e = \begin{cases} 1 & \text{if } e \in E \\ M & \text{if } e \in \bar{E} \end{cases} \tag{6}$$

Equation (1) represents the objective function of COP1, which minimizes the number of links that separate all centroids. Equation (2) defines the constraint on the labels of link e and its incident nodes (i, j). When link e is included in the cut, the corresponding node labels become $(k_i^q, k_j^q) = (0, 1)$. In contrast, when link e is not included in the cut, the labels of its two endpoints must be equal. Equation (3) constrains the label of the OD pair (s,t) to be $(k_s^q, k_t^q) = (0, 1)$. Equations (4) and (5), respectively, constrain the variables to be continuous and binary integers. The variable $l_e \mid e \in \dot{E}$ must be binary because the coefficient matrix associated with the left-hand side of Equation (2) is not totally unimodular, and thus the integrality of the solution cannot be guaranteed.

2.2 Formulation of the additional sensor location problem as an extension of COP1

In this section, we extend COP1 to derive the additional sensor location problem required for implementing screen-line observations, taking into account that some sensors are already installed on particular links. The links that already contain sensors in the initial state (termed pre-installed links) are given as input, and are denoted by $\tilde{e} \in \tilde{E} \mid \tilde{E} \subset E$. Suppose that $c_e = 0 \mid e \in \tilde{E}$. In this case, the number of additionally placed links, i.e., the objective function value, remains the same; however, multiple equivalent optimal solutions may emerge in which the number of pre-installed links included in the screen line differs. Such a solution represents a screen line consisting of a larger number of links. Placing sensors on a screen line that includes more pre-installed links may be undesirable when considering the maintenance costs of sensors. This can be taken into consideration by assigning a very small value ϵ to c_e. By setting $0 < \epsilon \ll 1$, we ensure that the decision regarding additional locations is not affected, and that only those pre-installed links necessary for forming the screen line are selected, $l_e = 1$. Specifically, it suffices that the increase in the objective function when sensors are installed on all links $\tilde{E}$ is smaller than the increase incurred by installing a sensor on a single link $e \in E$. In other words, we require $0 < \epsilon < \frac{1}{|\tilde{E}|}$.

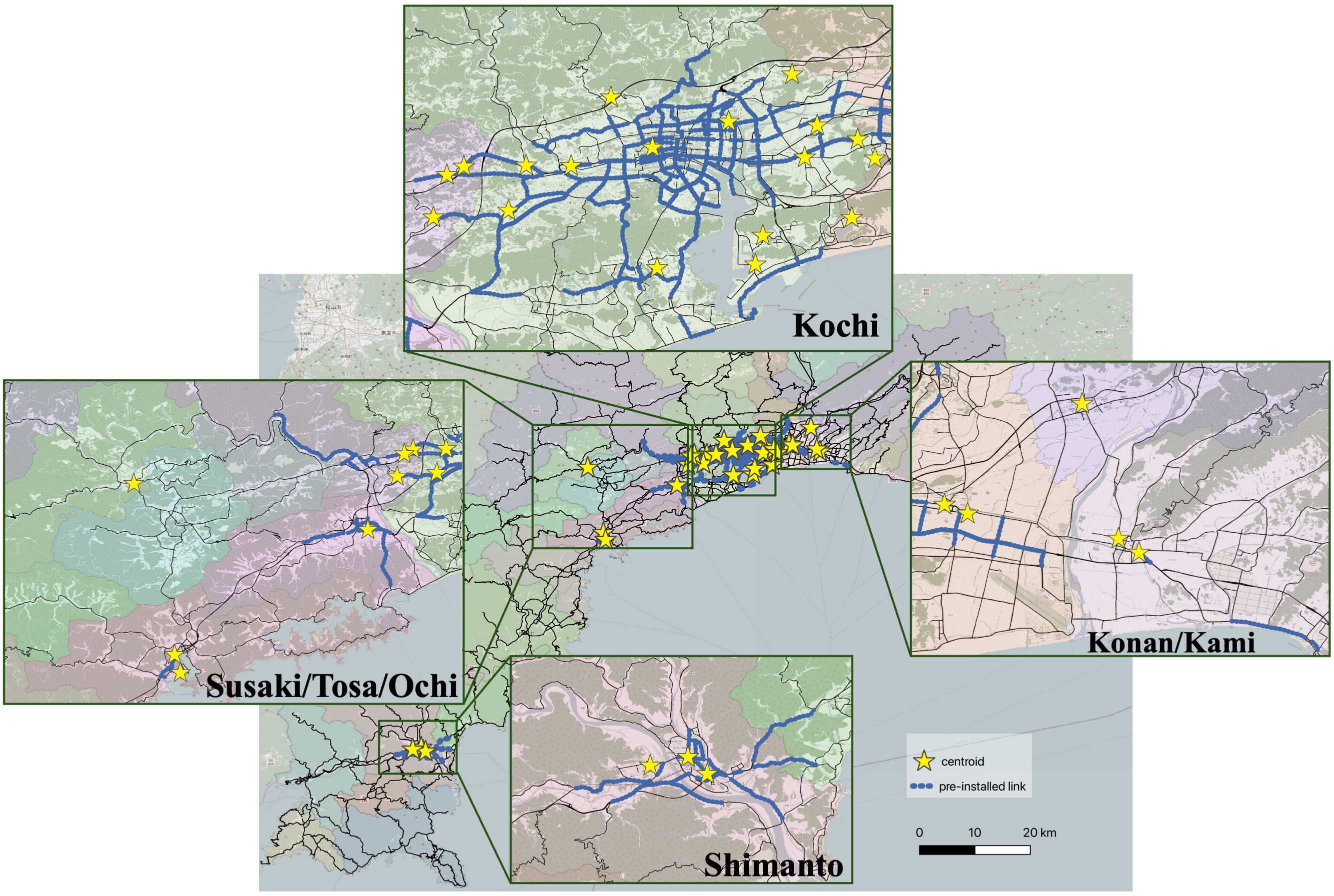


Fig. 2: Configuration of centroids and pre-installed sensor locations in Kochi road network.

Based on the above, the objective function of COP1 is modified as follows:

$$\min_{k,l} \sum_{e \in \dot{E}} \theta_e l_e \tag{7}$$

where

$$\theta_e = \begin{cases} \epsilon & \text{if } e \in \tilde{E} \\ M & \text{if } e \in \bar{E} \\ 1 & \text{otherwise} \end{cases} \tag{8}$$

That is, the problem with the objective function given by Equation (7), and with constraints (2)–(5) and (8) added, constitutes the additional sensor location problem as an extension of COP1. Hereafter, we denote this problem as COP1'.

3 Application to Kochi road network

3.1 Overview of data used

Using the COP1 and COP1' methods explained above, we analyzed the sensor location problem for screen-line observation in an actual road network. We selected Kochi Prefecture as the target area for analysis, which contains many rivers and, consequently, numerous bridges spanning them. Kochi City, the economic center of the prefecture, has a population of around 330,000 and a population density of around 1057 people/km^2, while Kami City, for example, has a population of around 27,000 and a population density of around 49 people/km^2 [14]. Thus, due to varying geographical conditions and differences in economic activity concentration, the road network consists of a diverse distribution of connection densities. Given these regional characteristics, the link sets constituting screen lines were expected to reflect these features. The road network data for Kochi Prefecture were obtained from OpenStreetMap [9] using OSMnx [3] by specifying highway tags including motorway, trunk, primary, secondary, and tertiary, and took the form of a directed network considering traffic direction.The resulting network consisted of 2,387 nodes and 6,697 links.

The locations of traffic-counting stations were taken from JARTIC's Cross-sectional Traffic Volume Information, detailed version B dataset [1]. Although the dataset records the flow direction at each station, directionality was omitted in the present study because of constraints in network preprocessing. Instead, the links geographically close to each observation point was treated as a "pre-installed" link. We judge that this simplification does not materially affect the interpretation of our results; however, if truly bidirectional observations become available, they would allow a more refined analysis. The procedure identified 812 pre-installed links in total. Next, centroids were set up to represent points in population-concentrated areas. Specifically, based on the 2015 population mesh data [2] , meshes with high population were extracted. Based on these extracted population-concentrated area meshes, 30 centroids were established on the road network near the centers of each such area. The locations of pre-installed links and centroids identified are shown in Figure 2.

3.2 Computational analysis

Using the data created through the procedure described in the previous section, the following three aspects were analyzed:

1. Identifying screen lines formed by pre-installed sensors and the OD pairs separated by these screen lines
2. Solving the SLTCLP without considering pre-installed sensors (COP1)
3. Solving the additional sensor location problem to establish screen-line observation, given the pre-installed sensors as conditions (COP1')

In this analysis, to prevent link sets directly connected to centroids from being designated as sensor-located links, nodes up to two adjacent away from each centroid were set as "deemed centroids." The original statement describes a challenge in traffic modeling where OD traffic volumes observed on screen lines cannot be solely attributed to centroids. Therefore, observing only links directly connected to centroids may not accurately capture the actual OD traffic patterns. The solution proposed is to make a simplifying assumption that traffic is generated and attracted in the areas surrounding the centroids. For this reason, COP1 and COP1' were calculated for dummy nodes representing these deemed centroids. The network operations described here are illustrated in Figure 3. However, for the set of deemed centroids corresponding to each centroid, we excluded other centroids and nodes included in the two-adjacent node sets of other centroids. In addition, in the computation of COP1', we set a very small value $\epsilon | 0 < \epsilon < \frac{1}{|\tilde{E}|}$.

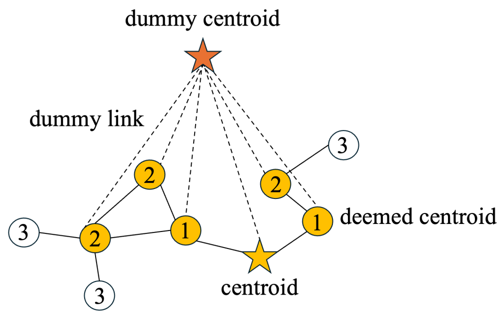


Fig. 3: Network setting with deemed centroids and dummy centroid representing the sum of the centroid and deemed centroids of the corresponding centroid

3.3 Computational results

3.3.1 Analysis 1. Relationship between the locations of the pre-installed sensors and the screen line

We analyzed the extent to which pre-installed sensors form screen lines between OD pairs. This can be evaluated by checking whether paths containing no pre-installed links exist between each OD pair. Specifically, we excluded pre-installed links from the overall road network, executed shortest path searches between OD pairs, and examined whether paths consisting of links not currently being observed existed. In this way, we found that 408 OD pairs (47%) out of a total of 870 (=30×29) OD pairs already had cut structures formed by pre-installed links. Considering that the screen-line requirement in SLTCLP is the strict condition of satisfying the constraint of observing all potential paths in the network at least once, it can be considered that the sensor location had already been established to form screen lines for many of the OD pairs.

Table 1 summarizes the observation rate of OD pairs captured by screen lines for each municipality in which centroids are located. Note that both the number of OD pairs and the number of observed OD pairs presented in Table 1 include all OD pairs in which either endpoint is associated with a centroid within the respective municipality. As a result, there is an overlap between municipalities, and the sum of OD pairs across municipalities does not match the total number of unique OD pairs. It is also worth noting that the number of centroids in each municipality is approximately proportional to the population distribution within the prefecture. From Table 1, it is evident that Kochi City contains about half of all the centroids, which results in its having a higher number of OD pairs and observed OD pairs. The observation rate of OD pairs in Kochi City is 48%, which is roughly the same as the overall average for the prefecture. Among all municipalities, Tosa exhibits the highest observation rate of 100%, followed by Shimanto. The lowest observation rates are observed in Nankoku, Susaki, Konan, Kami, and Ochi.

As shown in Figure 2, a large number of pre-installed sensor links are concentrated in the central area of Kochi City, while the number of such links in areas outside Kochi City, namely, suburban regions, is relatively small. As many of the links adjacent to centroids in the central area are already equipped with sensors, OD pairs involving these centroids are, in many cases, already separated under the current observation conditions. In contrast, some centroids located in the outer areas lack any surrounding pre-installed sensors, meaning that the separability of OD pairs involving these centroids depends on the observation status around the corresponding paired centroid. Focusing on Kami, although it contains a single centroid located in the central part of the municipality, it has no pre-installed sensors. This is the primary reason for its low OD pair separation rate. That is, the separability of OD pairs involving the centroid in Kami is entirely dependent on the observation status near the other endpoint of each OD pair.

From the above, it can be confirmed that the number of pre-installed sensors in each municipality of Kochi Prefecture is generally proportional to its population size. In Kochi City, the central urban area of the prefecture, a biased distribution of pre-installed sensors is observed between the city center and its suburbs. Nonetheless, there are regions where many OD pairs have already been separated under the current conditions. However, in municipalities with smaller populations, the number of sensor links is limited, and the separability of OD pairs involving centroids in these areas depends heavily on the observation conditions around the corresponding paired centroids.

3.3.2 Analysis 2: Results of the screen-line location problem without pre-installed sensors

First, the sensor location problem defined as COP1 was applied to the road network of Kochi Prefecture, assuming the predefined centroids. Figure 4 illustrates the resulting sensor-located links, which are highlighted in red. A total of 192 links were selected for sensor installation in the solution.

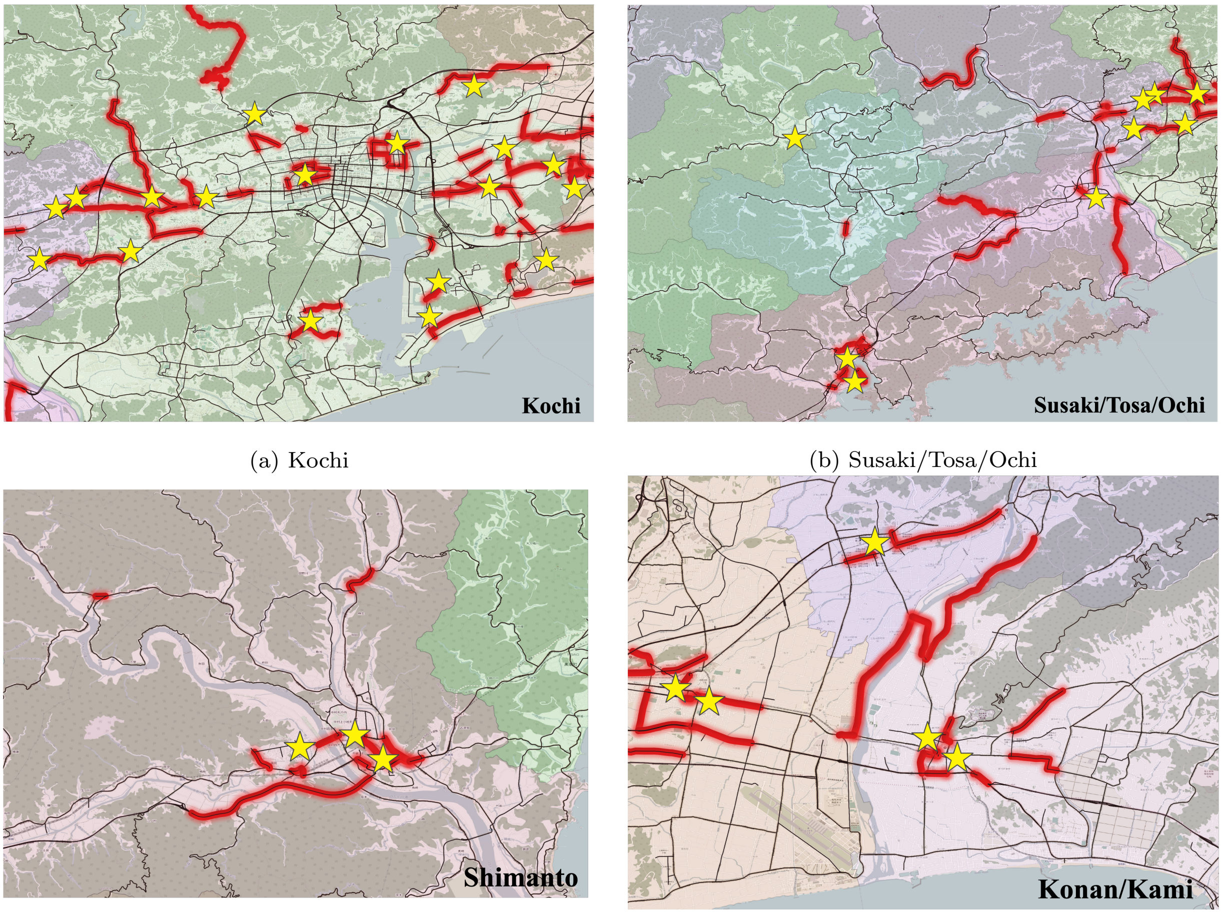
It can be observed that, due to the use of centroids, many of the selected links are located slightly away from the original centroids. However, in some areas, such as Kochi City and parts of Shimanto, centroids are densely clustered, preventing the assignment of deemed centroids. In these cases, links directly connected to the centroids were selected. Additionally, in areas such as Susaki, Tosa, Ochi, and parts of Shimanto, some selected sensor-located links are not adjacent to any centroid. In particular, in Susaki, Tosa, and Ochi, links located far from the centroids were selected. This indicates that these parts of the network have low path redundancy. In Shimanto, the structure of the road network is influenced by rivers, and certain bridge segments with limited redundancy were selected as sensor-located links.

These observations suggest that COP1 tends to form screen lines by selecting links that serve as bottlenecks in terms of OD path redundancy. Therefore, these results indicate that the solution to COP1 is significantly influenced by the topological structure of the road network, and the selected sensor locations are predominantly concentrated in areas with limited path redundancy.

3.3.3 Analysis 3. Results of the additional sensor locating problem with pre-installed sensors

Next, we present the results of solving COP1' under the condition that the pre-installed sensors are treated as fixed. The optimal solution consists of 111 pre-installed links and 110 additional sensor-located links. Compared with the 192 links selected in the solution to COP1, the total number of sensor-located links has significantly increased. This is because, while COP1 tends to select links directly connected to centroids or deemed centroids as optimal observation locations, COP1' selects additional links in such a way that they capture only the unobserved routes, given the pre-installed sensor coverage already distributed across the network. Therefore, the resulting screen lines include links that are not necessarily adjacent to centroids or deemed centroids. In contrast, compared with the case where all sensor locations are newly determined as in COP1, the number of newly required sensor locations is significantly reduced in COP1' by leveraging the pre-installed sensors.

Figure 4 illustrates the solution of COP1' in the Kochi Prefecture road network, i.e., the location of the pre-installed links and the additional sensor-located links. Note that the red links are the pre-installed and additional sensor-located links, which are the solutions of COP1' that do not distinguish the current location, the blue links are the pre-installed links in the current situation, and the red and blue overlapping links are the pre-installed links among the sensor-located links of the COP1' solutions. It can be seen that in many places, a set of links similar to the sensor-located links obtained in **Analysis 2** is selected for the additional sensors. The fact that the solutions for COP1 and COP1' are almost identical—because this solution aims to achieve



(a) Kochi

(b) Susaki/Tosa/Ochi

(c) Shimanto

(d) Kami/Konan

Fig. 4: Sensor-located links resulting from solution of COP1 in four regions

the screen lines with the minimum number of both pre-installed links and additional sensor-located links—means that the pre-installed links are inferred to have already partially achieved the screen line consisting of the minimum number of links.

However, there are some locations in various regions where a large number of additional sensor-located links are required. Table 2 shows the results of the number of pre-installed links and the number of additional sensor-located links for each municipality in the solution for COP1'. Note that there were 23 links where a single link spanned multiple municipalities, and these were duplicated and accounted for in each municipality. The overall data shown in the last line of Table 2 are the figures for the whole prefecture without considering this duplication.

As confirmed in **Analysis 1**, Kochi City has a large number of pre-installed links. Therefore, it is assumed that the screen lines were formed with a minimum of additional sensor-located links while making use of the pre-installed links. The additional sensor-located links in Kochi City account for only about 27% of the total links constituting the screen lines in the area, which is the lowest percentage except for areas that do not require additional sensor-located links. Similarly, in Shimanto, 44% of links are additional sensor-located links, which suggests that screen-line-like observations can be achieved with a small number of additional sensor-located links by taking into account the links that are initially observed. In contrast, in Nankoku, Ino, Susaki, and Tosa, more than half of the total number of links are additional sensor-located links, indicating the relatively high cost of achieving screen-line-like observations. The solutions for Konan, Kami, Sagawa, Niyodogawa, and Hidaka contain no pre-installed sensors at all. However, the installation cost is small because the number of additional sensor-located links needed is small.

The analysis results show that the number of additional links required depends strongly on the density of the pre-installed links, so that the additional locating cost is small in urban centers and along main roads,

Table 1: Number of centroids, OD pairs, and observed OD pairs by municipality

	centroids	OD pairs	observed OD pairs	rate
Kochi	14	630	300	0.48
Nankoku	3	168	48	0.29
Shimanto	3	168	126	0.75
Ino	3	168	86	0.51
Susaki	2	114	32	0.28
Konan	2	114	32	0.28
Tosa	1	58	58	1.0
Kami	1	58	16	0.28
Ochi	1	58	16	0.28
Total	30	870	408	0.47

Table 2: Solution of COP1' in Kochi Prefecture road network: pre-installed links and additional sensor-located links

	pre-installed	additional	additional ratio
Kochi	114	31	0.27
Nankoku	35	21	0.60
Ino	23	14	0.61
Konan	20	20	1.00
Shimanto	18	8	0.44
Susaki	14	11	0.79
Tosa	9	6	0.67
Kami	6	6	1.00
Kuroshio	2	0	0.00
Sagawa	1	1	1.00
Niyodogawa	1	1	1.00
Hidaka	1	1	1.00
Total	221	111	0.50

where there are many pre-installed links, while a large number of additional sensor-located links are required in outer fringe areas and suburban areas, where there are few pre-installed links.

3.4 Analysis of the effect of road type in the solution of COP1'

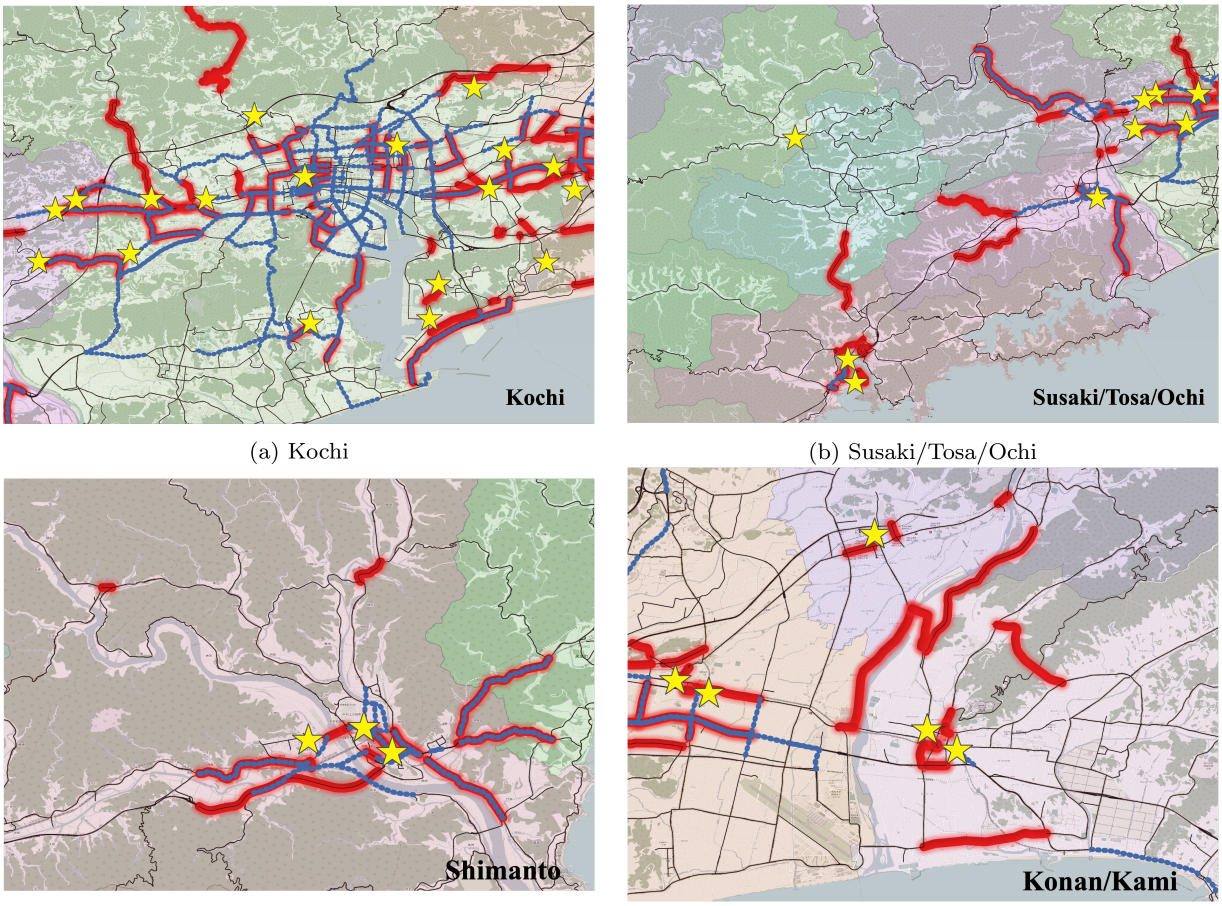
Then we examine the types of roads on which pre-installed and additional sensors are placed, based on the results of **Analysis 3**. Through this analysis, we discuss the configuration of link-based observation sensors required to achieve screen-line observation. Figure 6 focuses on the network obtained as a solution to COP1' in **Analysis 3** and presents the distribution of road types. From left to right, the figure shows the proportion of each road type for (1) all links, (2) pre-installed links, (3) pre-installed links included in the screen-line solution, and (4) additional sensor-located links included in the screen-line solution.

In the set of all links, municipal highways account for the largest proportion, followed by national highways and principal local roads. In contrast, within the set of pre-installed links, national highways represent the largest proportion, showing a significant increase compared with their share in the overall network. This indicates that the initial sensor deployment is primarily concentrated on national highways. Among the pre-installed links that are included in the screen-line solution, the proportions of motorway, national highway, and principal local roads are approximately consistent with their ratios in the initial observation set. However, the share of municipal highways is lower, which corresponds to an increase in the proportion of general prefectural roads. However, the additional sensor-located links included in the screen-line solution that were not part of the initial observation set show a different trend. Specifically, the proportion of national highways is significantly lower, while the proportion of general prefectural roads is noticeably higher. This can be attributed to the fact that the pre-installed sensors were concentrated on higher-order road types. As a result, additional sensor-located links were required on links belonging to lower-order road types, particularly those that were insufficiently covered in the initial deployment, to fully intercept OD routes missed by the pre-installed sensors' configuration.

The fact that the pre-installed sensors within the target road network were concentrated on higher-order road types implies that to achieve screen-line observation, it is necessary to also install sensors on links belonging to lower-order road types. Naturally, the objectives of link-based sensor observation are diverse. For example, from the perspective of monitoring traffic conditions on individual links, it is crucial to focus observations on high-traffic links where transportation policies may need to be implemented. However, if screen-line-based link observation can be achieved, it is possible to observe all routes between OD pairs, thereby enabling the estimation of OD traffic volumes. This, in turn, facilitates the implementation of policies targeting the entire road network. Therefore, as emphasized in this study, it is of significance to design sensor location strategies that also enable observation of lower-order road types, to make screen-line-based monitoring feasible.

4 Conclusion and discussion

We proposed an extension of SLTCLP1 to incorporate pre-installed sensors for practical analysis of real-world road networks. Based on this extended formulation, we presented an example analysis applied to an actual road



(a) Kochi

(b) Susaki/Tosa/Ochi

(c) Shimanto

(d) Konan/Kami

Fig. 5: Additional sensor-located links resulting from solution of COP1' and pre-installed links in four regions

network. Specifically, we formulated an extended version of COP1 as COP1' that preserves the mathematical structure of the original cut-based optimization model proposed by [13]. This extended model was applied to the road network of Kochi Prefecture, demonstrating its effectiveness for analyzing sensor location and screen-line observation in real-world networks.

Through the analysis presented in this paper, we provided insights into the characteristics of the solutions obtained from the extended model, particularly regarding the connectivity structure of the road network. The solution of COP1' retains this property while achieving screen-line observation by supplementing unobserved links with the minimum number of additional sensors, considering the pre-installed sensor configuration. Furthermore, the analysis focusing on the road types of links with pre-installed and additional sensors revealed that pre-installed sensors were installed on higher-order roads. As a result, the additional sensors required to achieve screen-line observation tended to be located on lower-order road types. These findings indicate that to realize screen-line observation, it is necessary to install sensors not only on links with pre-installed coverage but also on lower-order road types. Screen-line observation is considered highly valuable for implementing traffic policies from a network-wide perspective, and enabling its realization holds great importance. The insights gained from this study are expected to offer meaningful implications for future transportation planning and policy development.

One of the principal challenges for future research concerns data preparation. The road-network dataset employed in this study did not contain every existing road; in reality, the network is much denser. Accordingly, some routes that rely on finer-grained links may have been omitted when constructing screen lines between OD pairs. From a cost-efficiency perspective, however, surveying every conceivable route is seldom required. The appropriate level of network detail should be selected in light of practical needs and resource constraints. In addition, when mapping the locations of current traffic counters onto the road network, the di-

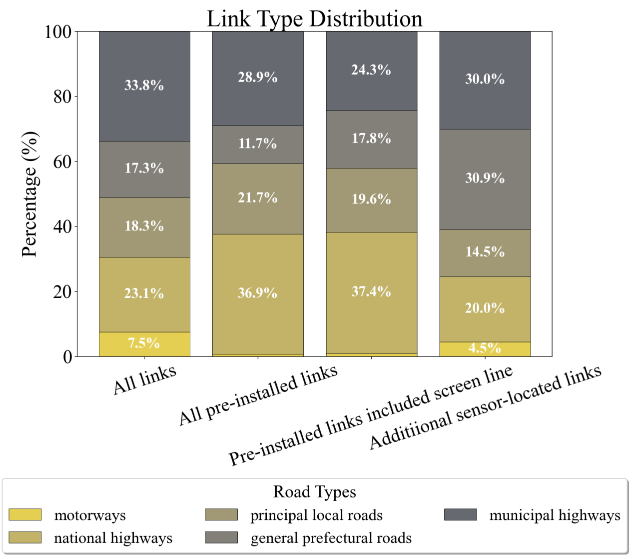


Fig. 6: Link type distribution of the Kochi road network

rectionality of observation was not taken into account. If data that include observation direction were available, more accurate analytical results could likely be obtained. Moreover, the solution to the SLTCLP is sensitive to the location of centroids. Determining their locations is thus a critical design choice that must be examined carefully. Taken together, these considerations are essential for interpreting the solutions obtained in this study and for guiding subsequent analyses.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Availability of data and materials Tha data set was obtained by Ministry of Land, Infrastructure, Transport and Tourism, Japan and OSMnx in this study. The data set is available to the public. There are no privacy restrictions.

Conflict of interest The authors declare that they have no conflict of interest.

Contributions **R.S**: Conceptualization, Methodology, Validation, Formal analysis, Visualization, Writing – Original Draft, **S.S**: Conceptualization, Methodology, Validation, Writing – Review and Editing, Supervision.

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