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Road Characteristic Based Location Technique for Vehicle Exhaust Gas Detection ⋆

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Abstract: Now there is a growing awareness that the air pollution in China is getting more and more serious, and the leading factor is the exhaust produced by vehicles in cities. To detect every registered vehicle enables us to take means to control the air pollution in cities. The conventional methods detecting exhaust by simulating running states, cannot capture the real-time emissions effectively. The remote sensing system for exhaust gas detection is an effective way to solve these problems. However, there is no location technique on how to place vehicle exhaust detecting devices in traffic network. This paper proposes a road characteristic based location technique for the devices. After determining the monitoring area and collecting the related road information, a model based on the road characteristics is established. Then these roads are clustered into several parts and the core roads will be the location. Finally the several schemes are evaluated, ranked and picked to achieve a relatively optimal location scheme.

Keywords: location technique, air pollution, vehicle exhaust, remote sensing system

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1. INTRODUCTION

Motor vehicle emissions contain CO, CO2, NOx, HC, PM, etc., causing respiratory and cardiovascular diseases such as asthma, bronchitis, stenocardia and coronary heart disease. One research by the Chinese Ministry of Environmental Protection shows that the exhaust gas contributes the majority of air pollutant in urban environment, especially by the *yellow-labelled cars*. The vehicle exhaust gas has increased the possibility of the occurrence of atmospheric haze and photochemical smog, making it an urgent task to resolve the vehicle emissions in the near future.

Conventional detection methods for vehicle emissions can be classified into four general categories, non-load test (under conditions of idle speed and double idle speed), driving mode test (including ASM, IM195 and VMAS), remote sensing monitoring and portable emissions measuring. They have been widely applied and are proven to be efficient. However, the off-line methods, measuring the exhaust gas by simulating running states, are unable to capture the real-time emissions effectively. This thus makes it necessary to design a remote sensing system for exhaust gas detection, capable of detecting the emissions of all vehicles when they are up and running. Such a system can be used for the automatic, real-time online monitoring, providing valuable information for vehicle emissions which can then be used for the government to design more pollution-aware policies.

Such a system is implemented by placing vehicle exhaust detecting devices on the roads which forms a detecting network. Not surprisingly the amount and location of the devices are key to the monitoring performance. Ideally the more detectors the system has, the better performance we can expect. However any realistic system is constrained by the economic considerations. Therefore, the balance between the cost and the performance, and consequently the optimization of the location of the detectors become one key technique in the remote sensing system.

Considerable works have been reported towards this goal from the traffic control perspective. Yang (1998) et al. analyzed the relationship between the quality of an estimated origin-destination matrix and the distribution of the sensors, resulting in a set of rules for optimizing locations. Bianco (2001) et al. set up a couple of greedy heuristics to find lower and upper bounds on the amount of sensors for a set of randomly generated networks. Ehlert (2006) et al. proposed two extensions to previous methods of great practical relevance by means of integer linear programming: one solution took existing detectors into account (referred to as the second-best solution), and the other took flow information from the prior OD into account. Gu (2005) et al. firstly studied the traffic sensor location problem using a minimum edge control set by modelling the traffic network as a digraph. Hu (2009) et al. solved the

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network sensor location problem independently by using the link-path incidence matrix to describe the network structure and then identifying its basis in a matrix algebra context rather than as a sub-problem of broader problems related to O-D demand estimation, time-dependent link travel time estimation, and operational consistency-seeking procedures.

However our problem here is slightly different from conventional sensor location problems for the traffic control purpose. Indeed, the purpose here is more to measure emissions of as many as vehicles at the minimum cost. To this end, a new technique based on the road characteristics is developed. In this technique the monitoring area is firstly selected and corresponding road information is collected. The roads are then clustered according to the internal similarity between them in the traffic network. The optimal scheme is obtained based on the final clustering of all the roads.

The rest of paper is organized as follows. Section 2 is devoted to the operating principle of three types of exhaust gas detecting devices and the location problem. Section 3 is concerned with the overall process of locating devices by clustering roads. Section 4 involves a simulation experiment to verify the effectiveness of the proposed technique. Section 5 concludes the paper.

2. DEVICE DESCRIPTION

We discuss the three types of detecting devices in the remote sensing system, as follows.

The horizontal exhaust detecting devices (HEDDs) are composed of an industrial controller, a speed/acceleration sensor, a traffic monitor, an exhaust gas detector and a license recognizer, as shown in Fig. 1. The traffic monitor (13) is placed above the roads, monitoring traffic conditions of 2 to 4 lanes at the same time. License information of passing vehicles are recognized and recorded by the license recognizers (12) over every lane. The exhaust gas detector (14) and speed/acceleration sensor (15) are placed on road-sides to measure the speed, acceleration and exhaust gas. The industrial controller (11) is employed for managing other components and processing data.

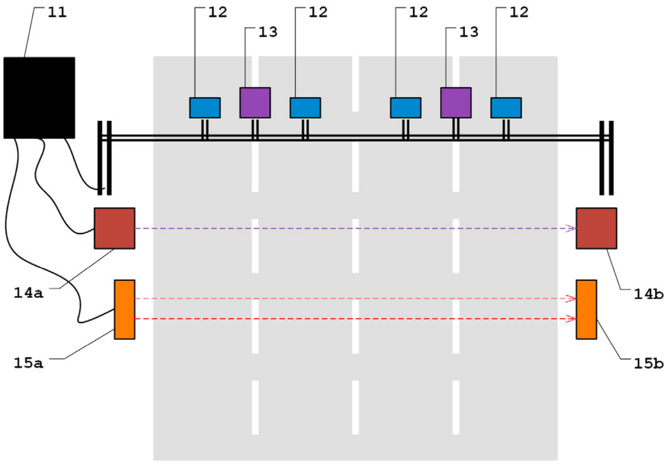

Fig. 1. An illustration of HEDD.

The vertical exhaust detecting devices (VEDDs) consist of an industrial controller, a speed/acceleration sensor, an exhaust detector and a license recognizer. The traffic monitor is not involved because detection for all lanes is independent. As shown in Fig. 2, the speed/acceleration sensor (13), the exhaust detector (14) and license recognizers (14) are mounted onto the metal support. The main difference between the HEDD and the VEDD is that the latter has an integrated emitter and receiver. The receiver receives the laser, which is generated by the emitter to the ground vertically, from the reflection area (15). Then the constituent and concentration of vehicle exhaust will be worked out according to the laser intensity reduction.

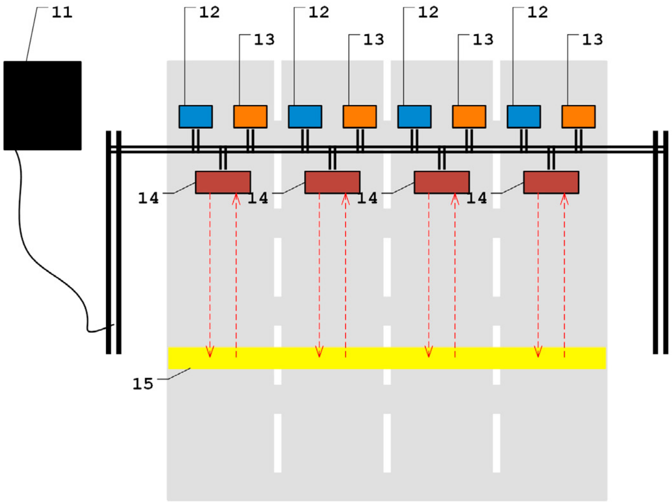

Fig. 2. An illustration of VEDD.

The transportable exhaust detecting devices (TEDDs), shown in Fig. 3, are composed of a monitoring car (11), an exhaust detector (13), a speed/acceleration sensor (14) and a license recognizer (12). With all the components in the monitoring car, the car can be driven to the roads where vehicles need to be detected temporarily. Some barricades (15) are required to guide the vehicles to drive through the device. The TEDDs work similarly as HEDDs.

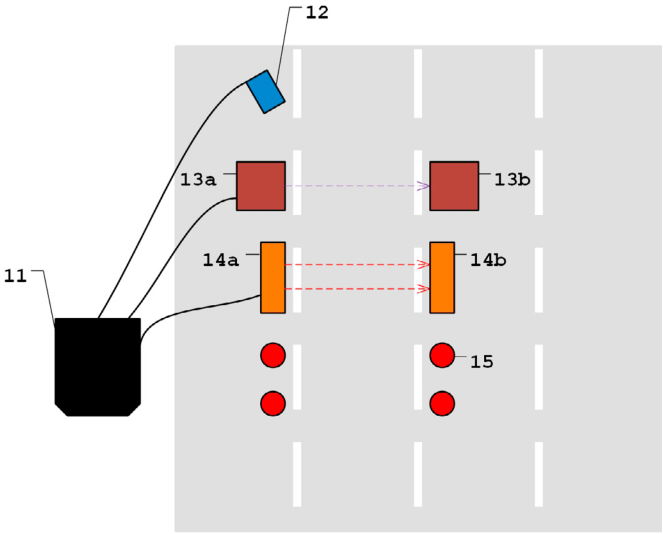

Fig. 3. An illustration of TEDD.

These exhaust detecting devices have their advantages and drawbacks. Despite the higher accuracy than VEDDs, HEDDs can only be used for light traffic, for it can fail if multiple vehicles are in parallel. On the other hand, TEDDs can be used where neither HEDDs nor VEDDs is appropriate.

3. ROAD CHARACTERISTIC BASED LOCATION TECHNIQUE

3.1 Urban traffic network modelling

The urban traffic network is modelled by a set of nodes and roads, $\{V, E\}$, where $V = \{v_1, v_2, \cdots, v_l\}$ is the set of nodes and $E = \{e_1, e_2, \cdots, e_n\}$ is the set of roads.

Many road characteristics can be described, such as the width, the number of lanes, traffic flow, etc.. For our purpose the road characteristics matrix is shown in Tab. 1.

Table 1. Characteristics Matrix

	e_1	e_2	$\cdots$	e_j	$\cdots$	e_n
y_1	x_{11}	x_{12}	$\cdots$	x_{1j}	$\cdots$	x_{1n}
y_2	x_{21}	x_{22}	$\cdots$	x_{2j}	$\cdots$	x_{2n}
$\vdots$	$\vdots$	$\vdots$		$\vdots$		$\vdots$
y_m	x_{m1}	x_{m2}	$\cdots$	x_{mj}	$\cdots$	x_{mn}

where $Y = \{y_1, y_2, \cdots, y_m\}$ is the set of all the registered vehicles, being the characteristics of roads E. x_{ij} is Boolean value determined by

$$x_{ij} = \begin{cases} 1, & \text{Vehicle } y_i \text{ passing on road } e_j \text{ during a period} \\ 0, & \text{otherwise} \end{cases}$$

Thus, $\sum_{i=1}^{m} x_{ij}$ indicates how many different vehicles pass on road e_j in a period. Euclidean distance is used to describe the difference between two roads, i.e.,

$$d_{ij} = d(e_i, e_j) = \sqrt{\sum_{k=1}^{m} (x_{kj} - x_{ki})^2}$$

The distance matrix $D_{n\times n}$ is defined as

$$D = \begin{pmatrix} 0 & & & \\ d_{21} & 0 & & \\ \vdots & \vdots & \ddots & \\ d_{n1} & d_{n2} & \cdots & 0 \end{pmatrix}$$

which is symmetric.

3.2 Clustering Analysis

Clustering analysis is a multi-variable statistical method for sample classification, and can be used here. It works in the following way. First the roads are roughly classified into several clusters according to experience. One core road should be determined for every cluster. Then the clusters are corrected by the minimum distance criterion until a reasonable classification is achieved.

The first step is to select core roads, which determine the original classification and affect the final classification.

The set of k initial core roads is

$$L^{(0)} = \{e_1^{(0)}, e_2^{(0)}, \cdots, e_k^{(0)}\}$$

All roads are classified based on

$$G_i^{(0)} = \{e : d(e, e_i^{(0)}) \le \mathrm{d}(e, e_j^{(0)}); i, j = 1, 2, \cdots k; j \ne i\}$$

to obtain k non-intersect clusters as

$$G^{(0)} = \{G_1^{(0)}, G_2^{(0)}, \cdots, G_k^{(0)}\}$$

The principle here is that roads should be classified into the cluster with the minimum distance.

From $G^{(0)}$ a new set of core roads

$$L^{(1)} = \{e_1^{(1)}, e_2^{(1)}, \cdots, e_k^{(0)}\}$$

is obtained, where $e_i^{(1)} = \frac{1}{n_i} \sum_{e_l \in G_i^{(0)}} e_l$ with n_i being the road amount in $G_i^{(0)}$. From $L^{(1)}$,

$$G_i^{(1)} = \{e : d(e, e_i^{(1)}) \le \mathrm{d}(e, e_j^{(1)}); i, j = 1, 2, \cdots k; j \ne i\}$$

yields

$$G^{(1)} = \{G_1^{(1)}, G_2^{(1)}, \cdots, G_k^{(1)}\}$$

Repeating these calculations it is obtained that

$$G^{(s)} = \{G_1^{(s)}, G_2^{(s)}, \cdots, G_k^{(s)}\}$$

with the set of core roads $L^{(s+1)}$. The classification will not change with s getting large. The classification is completed when the error

$$\Delta = \sum_{i=1}^{k} d(e_i^{(s)}, e_i^{(s+1)})$$

becomes smaller than a given threshold.

The road with the largest traffic flow in every cluster is selected to be the location. The principle for devices selection is as follows: the TEDD is used if neither HEDD nor VEDD is available; otherwise the VEDD is preferred for the heavy traffic and HEDD for the light.

3.3 Scheme Decision

The schemes obtained by clustering roads have their advantages and drawbacks. The balance between the cost and the performance then forms a multiple-attribute decision making problem. It is solved in two steps. First is the information collection and then the decision making.

The concerned attributes are shown as follows.

1) loss ratio u_1: is the proportion of vehicles that are not detected. It is the primary attribute.

2) cost u_2: is of the unit *million yuan*, and is the second important attribute.

3) schedule u_3: is of the unit *days*. Some devices are difficult to assemble or even block the traffic and thus the schedule must be taken into consideration.

4) reliability u_4: describes the capability of continuous operation. There are 5 degrees. They are extreme high (EH), high (H), medial (M), low (L) and extreme low (XL).

For the set of schemes $A = \{a_1, a_2, \cdots, a_q\}$ the set of attributes $U = \{u_1, u_2, u_3, u_4\}$ is used to measure and obtain the decision matrix $D_{q\times 4}$ as shown in Tab. 2.

Notice that u_1, u_2, u_3 are cost-type attributes and u_4 is benefit-type one, and therefore the dimensions of them are different. Normalization

$$r_{ij} = \begin{cases} \dfrac{v_{ij} - \min\limits_i\{v_{ij}\}}{\max\limits_i\{v_{ij}\} - \min\limits_i\{v_{ij}\}}, & \text{for benefit-type attribute} \\ \dfrac{\max\limits_i\{v_{ij}\} - v_{ij}}{\max\limits_i\{v_{ij}\} - \min\limits_i\{v_{ij}\}}, & \text{for cost-type attribute} \end{cases}$$

should be conducted.

Table 2. Decision Matrix

	u_1	u_2	u_3	u_4
a_1	v_{11}	v_{12}	v_{13}	v_{14}
a_2	v_{21}	v_{22}	v_{23}	v_{24}
$\vdots$	$\vdots$	$\vdots$		$\vdots$
a_q	v_{q1}	v_{q2}	v_{q3}	q_{24}

The related weights $\{w_i, i = 1, 2, 3, 4\}$ for these attributes are determined by the KLEE method. Its procedure and results are shown in Tab. 3.

Table 3. Weights Determining Procedure and Results

attribute	1	2	3	4	5	6	score	weight
u_1	1	1	1				3	0.40
u_2	0			1	1		2	0.30
u_3		0		0		1	1	0.15
u_4			0		0	1	1	0.15
summation	1	1	1	1	1	2	7	1.00

Finally concentrating these factors using

$$z(a_j) = \sum_{i=1}^{4} w_i u_i$$

to evaluate every scheme, ranking them from large to small, a relatively optimal location scheme for detectors is then worked out.

4. SIMULATION TESTS

4.1 Data collection

Data collection is based on the following: 1) roads are divided into main roads (MR), secondary roads (SR) and branch roads (BR). 2) vehicles are divided into two categories, long-distance and short-distance. The procedure is described as follows, in three steps.

Step 1: The proportions and distribution of MR, SR and BR are determined as "MR:SR:BR=1:4:8" and "BR-SR-MR-SR-BR=4-2-1-2-4" (similar to Gaussian distribution) in the simulation.

Step 2: Distribute vehicles onto roads with the proportion of "MR:SR:BR=4:2:1" and expand them to 5 areas. The resulting distribution is obtained as in Fig. 4.

Step 3: Let the vehicles be driven randomly then we get a new distribution as shown in Fig. 5. The appearance of 200 vehicles are distributed to 65 roads.

4.2 Results

Using the location technique proposed in this paper, 7 schemes are obtained as shown in Tab. 4, coupled with the decision matrix $D_{7\times4}$. The numbers in the column of *Location* are the roads' labels, meaning that the detectors should be placed on these roads, and the superscript $*$ for HEDDs, $**$ for TEDDs, and vacant superscript for VEDDs.

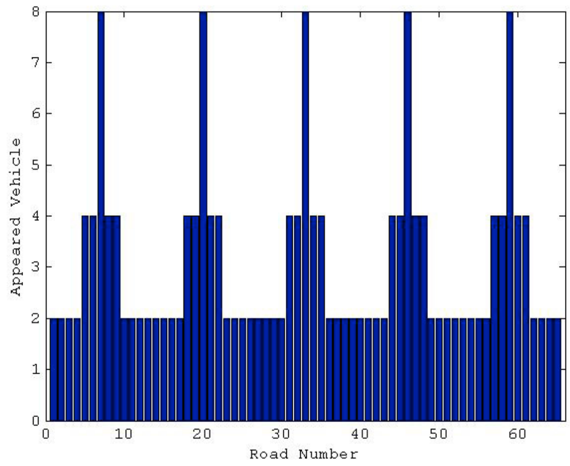

Fig. 4. Vehicle Distribution in Roads

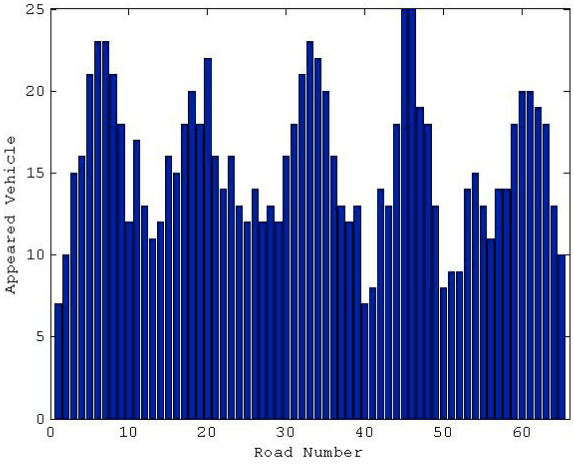

Fig. 5. Vehicle Appearance in Roads

Normalizing the decision matrix $D_{7\times4}$ yields another decision matrix $R_{7\times4}$ shown in Tab. 5.

Concentrating the attributes u_i yields

$$\begin{aligned} z(a_1) &= 0.4500 \\ z(a_2) &= 0.5145 \\ z(a_3) &= 0.5360 \\ z(a_4) &= 0.5495 \\ z(a_5) &= 0.5930 \\ z(a_6) &= 0.5320 \\ z(a_7) &= 0.5500 \end{aligned}$$

Ranking a_i based on $z(a_i)$ from large to small,

$$a_5 \succ a_7 \succ a_4 \succ a_3 \succ a_6 \succ a_2 \succ a_1$$

Hence Scheme 5 is the best, i.e., 1 TEDD, 2 HEDDs and 3 VEDDs are placed on Road No. 6, 20, 31, 33, 45, 60, respectively.

Table 4. Schemes and Decision Matrix

Scheme	Location	loss ratio u_1	cost u_2	schedule u_3	reliability u_4
a_1	6, 45	0.76	10	45	XL
a_2	6, 20*, 45	0.65	13	50	L
a_3	6, 20*, 45, 60*	0.55	16	55	L
a_4	6, 20*, 33, 45, 60*	0.44	21	65	M
a_5	6, 20*, 31**, 33, 45, 60*	0.40	23	65	H
a_6	6, 20*, 31**, 33, 45, 60*, 61*	0.39	26	70	H
a_7	6, 20*, 32**, 33, 45, 54*, 60*, 62*	0.31	29	80	XH

Table 5. Normalized Decision Matrix

Sch.	u_1	u_2	u_3	u_4
a_1	0.00	1.00	1.00	0.00
a_2	0.24	0.84	0.86	0.25
a_3	0.47	0.68	0.71	0.25
a_4	0.71	0.42	0.43	0.50
a_5	0.80	0.32	0.43	0.75
a_6	0.82	0.16	0.29	0.75
a_7	1.00	0.00	0.00	1.00

5. CONCLUSIONS

A road characteristic based location optimization method is proposed for the implementation of the remote sensing system for monitoring vehicle exhaust gas. Simulations illustrate its effectiveness. The work is preliminary with limitations, such as the simple Boolean assumption of the vehicle passing, and the ad hoc way of determining the weight w_i. More efforts will be given for a more practical method in the near future.

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