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Data Mining and Urban Road Traffic Analysis Based on Traffic Camera Data

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Abstract: Based on traffic data collected by cameras, this paper introduces the traffic analysis method for roadway design and data mining algorithms and explores their applications in urban transportation planning, infrastructure construction, and traffic management at macro-, mesa-, and micro-levels. Based on the spatial and temporal sequences of vehicles, three analysis tasks and solution methods are proposed to obtain three important indexes, namely the traffic flow distribution among adjacent areas, vehicle trajectories, and the time-dependent traffic operations. The concept of traffic flow distribution among adjacent areas is proposed. It refers to the traffic volumes between two adjacent areas connected by roads, and it reveals the macroscopic distribution feature of traffic flows. The application of frequent sequence mining algorithms can identify the sequences of vehicle clusters passing by the data collection cameras, which reveals the travel areas and paths of vehicle clusters. Based on the vehicles entering and egressing time, the travel time by hour of the day can be calculated. Finally, taking Yichang city in Hubei province as a case study, the paper illustrates the data mining and road traffic analysis framework based on traffic camera data. **DOI:** 10.13813/j.cn11-5141/u.2019.0114-en

Keywords: traffic engineering; traffic camera data mining; vehicle license plate matching; traffic flow distribution among adjacent areas; vehicle trajectories; time-dependent road operational level

0 Introduction

Traffic flow, travel speed, density, capacity and travel delay are important indicators for the evaluation of level of service of urban roads, road congestion level, implementation of transportation infrastructures, and traffic management. To obtain these indicators, the following survey methods are commonly adopted: car following method, floating car method (based on GPS), test vehicle method, manual observation, mechanical observation (sensors), video and aerial photography, etc. Based on existing survey methods, we can acquire a hierarchy of indices [1], such as the traffic flow indices, the travel speed indices, the road capacity indices, and the travel delay indices.

As the electronic traffic devices developed rapidly, there are more means for road traffic survey. The accuracy of obtained indicators is improved, and the hierarchy of indices is expanded. In recent years, the electronic traffic devices that can collect large amount of comprehensive data have been widely deployed [2], one of which is the road HD camera monitoring system. The HD cameras are installed at check points on highways, urban expressways and urban arterials, which shoot photos when vehicles pass and upload the data on-line to the database. The data includes the locations of the vehicles (i.e., the locations of the check points), the time when the vehicles passed the check points, the license plates of the vehicles, and the types of the vehicles (i.e., bus, private car). The data is real-time recorded, large-sized, and reliable. Currently, the data is analyzed and used to identify the target vehicles, such as vehicles that broke traffic laws, vehicles with fake license plates, and suspicious vehicles that conducted illegal activities [3]. Nevertheless, with data fusions of the vehicle locations, passing times, license plates and vehicle types, we can not only obtain the traditional road traffic indicators (e.g., traffic flow, travel time, and delay) but also derive new macroscopic and mesoscopic traffic indicators which cannot be obtained by traditional means, such as the vehicle trajectory indicators and inter-area traffic flows. The road traffic indicators obtained from the data can be applied to various aspects, including urban road system planning, road traffic design, and road traffic management [4]. Since the data carries an abundance of information, we must consider the following fundamental questions: which analysis tasks shall be designed, which road traffic indicators shall be obtained, and which solution methods can realize the tasks.

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1 Camera data analysis

The camera database contains at least the following fields: the camera ID, the shooting time, the license plate of the passing vehicle, and the vehicle type. Because the locations of all cameras are known and fixed, the camera ID can be seen as a check point with coordinates. Through conducting statistical analysis based on each field in the database [5], we can obtain regular traffic survey indicators such as the road traffic flow, distribution of vehicle types, and distribution of vehicle registration locations. The data is grouped by license plate and the check points and shooting times are arranged in chronological order. Then, the check point sequences and the corresponding time sequences of all vehicles can be obtained.

Based on the Hadoop framework, we can use JAVA programming tools to analyze the check point sequences and time sequences of vehicles and obtain some road traffic indicators which cannot be obtained by traditional traffic survey methods. Firstly, the check point sequence of a vehicle reflects the areas that it passed. Counting the number of area crossings made by all the vehicles, we can obtain the macroscopic inter-area traffic flows. Secondly, the check point sequences and time sequences reflect the vehicles' trajectories. Frequent pattern mining is applied to the check point and time sequences of selected vehicles, and then we can find the places where these vehicles mainly came from and went to and the frequent routes they take. Thirdly, based on the check point and time sequences of the vehicles passing a selected road, we can obtain the travel time data of the road and the corresponding time of day data and further acquire more traffic indicators such as the average free-flow travel time, average peak hour travel time, TTI index (1), daily average speed, and maximum travel time difference at the same time of day. This study uses Yichang City, Hubei Province, China as the case study (2) to illustrate the data analysis and solution methods.

2 Inter-area traffic flows

The city is divided into several areas. For any two adjacent areas connected by roads, the number of vehicles traveling from one area to the other during the analysis period is a directed inter-area traffic flow. The inter-area traffic flow matrix, which contains the directed traffic flows between all adjacent and road-connected areas, is an $n \times n$ matrix (n is the number of areas). The matrix element $v_{i,j}$ is the directed traffic flow from area i to area j. If area i is adjacent to area j and they are connected by roads, then $v_{i,j} \geq 0$; otherwise, $v_{i,j} = 0$. The inter-area traffic flow matrix cannot be obtained by traditional traffic survey methods. The method to obtain the inter-area traffic flow matrix based on the check point sequences is illustrated below.

Each check point is in an area. The check point sequence of a vehicle can be mapped to an area sequence. In Figure 1, the solid black lines represent the roads; the black dotted lines represent the area borders; and the curves with arrows represent the vehicle trajectories. The check point sequence of the vehicle in Figure 1 is HJKA, and the mapped area sequence is ①④⑧⑤.

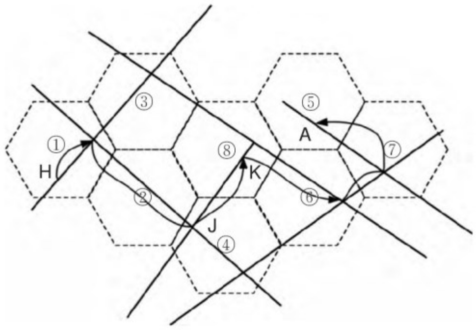


Figure 1 Example of check point sequence and area sequence of a vehicle

The area sequences of vehicles must be corrected before counting the inter-area traffic flows. The objective of correcting the area sequence is to check whether the area sequence lacks any areas in which the vehicle was missed by the cameras. If so, we have to find out the missed areas and add them to the area sequence. There are two principles to check whether a vehicle was missed by the cameras when it passed some areas. One principle is that a vehicle shall not be spotted successively in two non-adjacent areas. Another principle is that a vehicle shall not be spotted successively in two adjacent areas without road connections. Based on these two principles, for any two consecutive areas in an area sequence, the following should be checked. 1) Criterion 1: the two areas are adjacent. 2) Criterion 2: the two areas are connected by roads. Assuming all vehicles select the shortest routes, the procedures to correct an area sequence are as follows: 1) for any two consecutive areas in the area sequence, check whether they satisfy both Criteria 1 and 2. If not, go to next step; 2) the missed areas between these two areas are found based on shortest path algorithm [6]. Figure 1 is taken as an example. Area ① and Area ④ are not adjacent to each other, so Area ② must be added between them. Area ⑧ and Area ⑤ are adjacent to each other but not connected by roads, so Area ⑥ and Area ⑦ must be added between them. The area sequence before correction is ①④⑧⑤, and the corrected area sequence is ①②④⑧⑥⑦⑤. In the corrected area sequence of a vehicle, any two consecutive areas indicate that there is one-unit traffic between these two areas (the order of the two consecutive areas indicates the direction of the one-unit traffic). Based on the corrected area sequences of all vehicles, the inter-area traffic flow matrix can be obtained by counting how many times that any two adjacent and road-connected areas appear as consecutive areas in all area sequences.

The inter-area traffic flow graph can be obtained based on the inter-area traffic flow matrix. For example, Figure 2 shows the inter-area traffic flow graph of downtown Yichang City, Hubei Province, China. The total number s_i of vehicles entering Area i can be obtained by adding all the elements in the i^{th} row of the inter-area traffic flow matrix. The total number d_i of vehicles leaving Area i can be obtained by adding all the elements in the i^{th} column of the inter-area traffic flow matrix. $s_i + d_i$ is defined as the traffic activity level of Area i, with larger value for higher traffic activity of Area i. The traffic activity level of an area can be graded. The red parts in Figure 3 are the areas with high traffic activity levels in downtown Yichang City. The elements $v_{i,j}$and $v_{j,i}$ in the inter-area traffic flow matrix are the two directed traffic flows between Area i and Area j, and their ratio (the larger one to the smaller one) is defined as the inter-area traffic balance coefficient. The minimum value of the inter-area traffic balance coefficient is 1, which means that the two directed traffic flows between two areas are the same. The larger inter-area traffic balance coefficient can result in the less balanced two directed traffic flows. With Yichang City as an example, the inter-area traffic balance coefficients for most two areas are within 1.2, which means that the two directed traffic flows between most two areas are basically balanced. The traffic capacity $c_{i,j}$ from Area i to Area j can be obtained by the summing up the traffic capacities of all roads from Area i to Area j. The ratio $(v_{i,j}/c_{i,j})$ is defined as inter-area traffic service level, which is one of the bases for judging whether the road connections between two areas are sufficient or not.

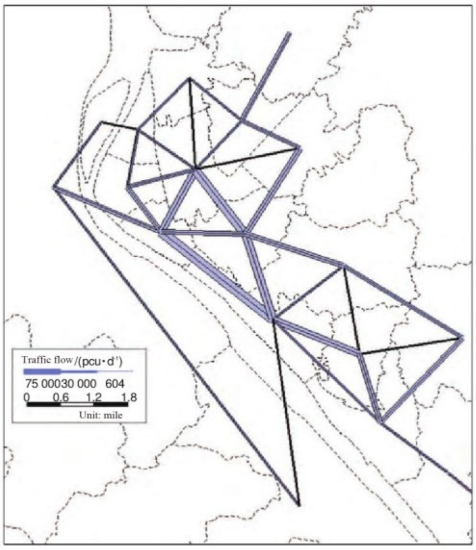


Figure 2 Inter-area traffic flow of Yichang central districts

In summary, by analyzing the check point sequences of vehicles, we can obtain the inter-area traffic flow matrix, the inter-area traffic flow graph, traffic activity level of an area, inter-area traffic balance coefficient, inter-area traffic service level, etc.

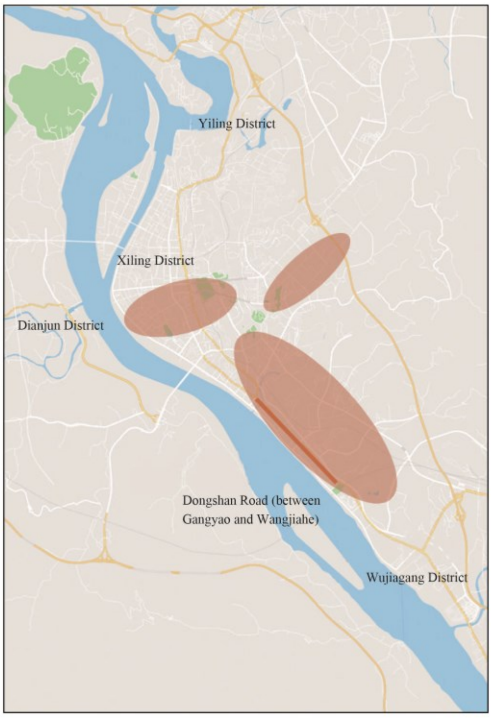


Figure 3 Road traffic-active areas in Yichang central districts

3 Analysis of traffic flow trajectory

Based on the sequences of vehicle check point and time sequences, we can find those check points which a particular group of vehicles passed frequently and the frequent sequences by which the vehicles passed these check points. The check points that the vehicles frequently passed reflect the areas where the vehicles are often in, and the frequent sequences reflect the key routes taken by the vehicles. The analyst selected the group of vehicles that passed a specific check point during the analysis period. The analyst then obtained the places where the vehicles came from before they reached the specific check point and where they went to after they left the specific check point and got the key routes taken by the vehicles before reaching and after leaving the specific check point.

An analysis period and a time threshold m-min are defined. It is assumed that the specific check point A is equipped with a HD camera. Analysis is conducted on every vehicle's check point sequence. If a vehicle's check point sequence contains A and the corresponding camera shooting time is within the analysis period, this vehicle is marked. For example, a vehicle's check point sequence is HJKASHSK, and the corresponding time sequence is $t_1t_2t_3t_4t_5t_6t_7t_8$. t_4 is within the analysis period, and then this vehicle is marked. We apply time constraints on the vehicle's check point sequence by only keeping those check points whose camera shooting time are within the m-min interval of check point A's shooting time. For example, it is assumed that t_1, t_7 and t_8

are not within the m-min interval of t_4, and then the first, the seventh, and the eighth check points in the check point sequence HJKASHSK shall be removed, so the remaining check point sequence is JKASH. In this sequence, the sub-sequence which contains check point A and those prior to check point A is defined as the vehicle's upstream sub-sequence, and the sub-sequence which contains check point A and those posterior to check point A is defined as the vehicle's downstream sub-sequence. For example, the upstream sub-sequence for the marked vehicle is JKA and the downstream sub-sequence is ASH.

The first element of the upstream sub-sequence of a marked vehicle indicates where the vehicle came from within m minutes before it reached the specific check point. The last element of the downstream sub-sequence indicates where the vehicle arrived within m minutes after it left the specific check point. Based on the upstream sub-sequences of all selected vehicles, the m-min traffic origin proportion of a check point is defined as the ratio of the number of occurrence that the check point is the first element of upstream sub-sequences to the number of all selected vehicles. Likewise, based on the downstream sub-sequences of all selected vehicles, the m-min traffic destination proportion of a check point is defined as the ratio of the number of occurrence that the check point is the last element of downstream sub-sequences to the number of all selected vehicles. Calculating the m-min traffic origin proportions of all check points gives us the m-min origin distribution of the selected vehicles. Calculating the m-min traffic destination proportions of all check points gives us the m-min destination distribution of the selected vehicles. We can then further know which places are the important m-min origins and destinations.

Frequent pattern mining is performed on the upstream sub-sequences and the downstream sub-sequences of the selected vehicles, and association rules are formulated [7]. The check point fragments, whose number of occurrence in the upstream sub-sequences exceed the custom-made threshold, reflect the m-min important from-routes the vehicles take before they arrive the specific checkpoint, and they are defined as the m-min frequent upstream check point fragments. Likewise, those fragments, whose number of occurrence in the downstream sub-sequences exceed the threshold, reflect the m-min important go-routes the vehicles take after they leave the specific checkpoint and are defined as the m-min frequent downstream check point fragments. With the GSP algorithm, all the m-min frequent upstream and downstream check point fragments can be obtained. All m-min frequent upstream and downstream check point fragments are illustrated by the branch diagram. With Figure 4 as an example, m-min frequent upstream check point fragments include UFGA, FGA, GA, WTGA, TGA,QTGA and EGA, which represent the m-min important from-routes. The check point fragments of m-min frequent downstream include AH, AHL, AHM, AHMP, AJ, AJN, AJK and AJKR, which represent the m-min important go-routes.

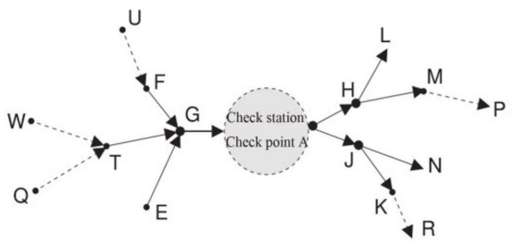
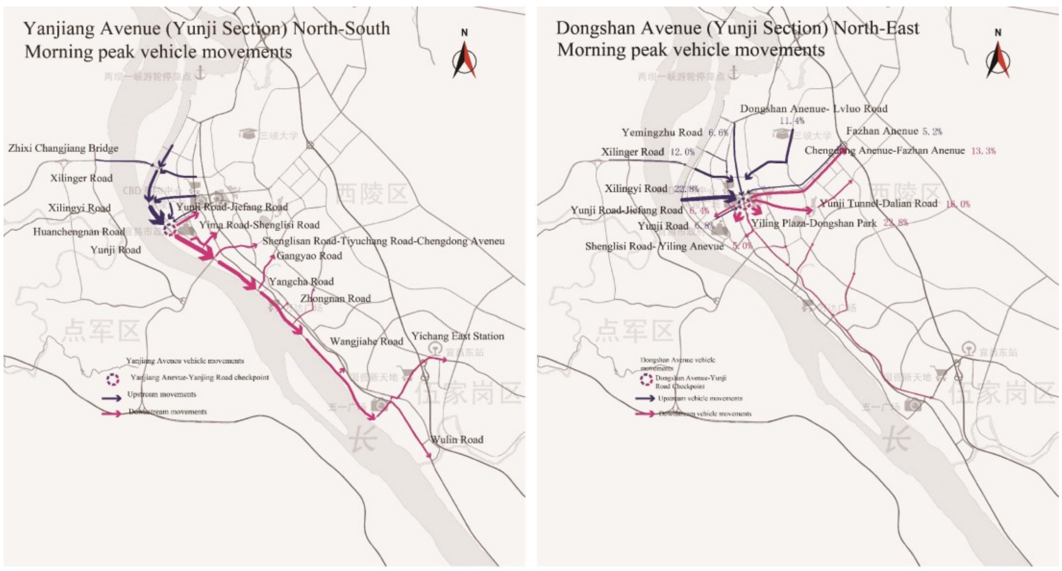


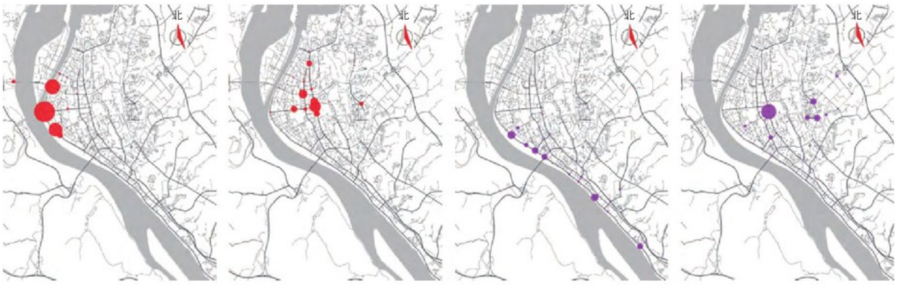
Figure 4 Branch diagram of m-min frequent upstream and downstream check point sub-sequence



a From-and-go routes of vehicle groups Q1

b From-and-go routes of vehicle groups Q2

Figure 5 15-min frequent from-and-go routes of vehicle groups Q1 and Q2



a Origin of Q1　　b Origin of Q2　　c Destination of Q1　　d Destination of Q2

Figure 6　15-min origin and destination distributions of vehicle groups Q1 and Q2

Yichang city is taken as an example. The intersection of Yunji Road and Yanjiang Avenue is chosen, namely check point A, as the first specific check point. The intersection of Yunji Road and Dongshan Avenue is selected, namely check point B, as the second specific check point. The selected vehicles are two groups of vehicles: 1) vehicles of group Q1 which passed check point A and traveled along Yanjiang Avenue from north to south; 2) vehicles of group Q2 which traveled along Dongshan Avenue from north to south. Figures 5(a) and (b) show the 15-min important from-routes and go-routes of vehicles of groups Q1 and Q2, respectively. Figures 6(a), (b), (c), and (d) show the 15-min origin and destination distributions of vehicles of groups Q1 and Q2, respectively. For the vehicles that pass check point A from north to south, most of them come from the northern river-side and cross-river areas and choose the Yanjiang Avenue and then go to the southern river-side areas or left downtown. For the vehicles that pass check point B from north to south, they come from multiple areas in the central and go to multiple areas as well. This case suggests that Yanjiang Avenue mainly serves the drivers who make long-distance travels by the river-side. Dongshan Avenue serves the drivers who make short-distance travels in the central areas.

In summary, based on the analysis of check point sequences of selected vehicles, we can obtain the *m*-min origin distributions, the important origin areas, and the important from-routes of the selected vehicles before they reach the specific checkpoint. We can also obtain the *m*-min destination distributions, the important destination areas, and the important go-routes of the selected vehicles after they leave the specific check point.

4　Analysis of road operation

Based on the check point sequences and time sequences of the vehicles that passed a selected road, the travel time of that road and the time of the vehicles exited the road can be obtained. Then we can conduct analysis on the operation of the selected road. The prerequisite is that cameras are installed at both the entrance and exit of the selected road. The urban expressway in Figure 7 is taken as an example. Cameras are installed at the entrance (check point A) and exit (check point B) of the road. Cameras may also be installed at other check points (e.g., at check points C and D). Conditional judgment is made on the check point sequence of every vehicle, namely whether the check point sequence of the vehicle contains fragment ACDB or not. If so, the vehicle must have passed the selected road and its travel time passing the road is recorded, which is the time difference between the time when the vehicle was at check point B and check point A. The time that the vehicle exited the road is also recoded (when the vehicle was at check point B), which is the time of day that the travel time is corresponding to.

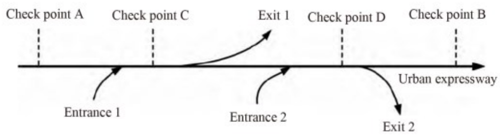


Figure 7　Check points on urban expressway

The travel time of the selected road and the corresponding time of day can be obtained by the above method and then form a data set φ. However, noise data may be included because some vehicles may not travel from the check point A to check point B directly but leave and re-enter the road somewhere between check point A and B (such as the other entrances and exits in Figure 7) after a while. In these cases, the travel time and time of day data are noise data and must be deleted from the data set; otherwise the data analysis results will not be accurate. This study proposes a data cleaning algorithm, which has two steps. Step 1: Delete the data whose travel time is too high or too low during a day. For example, if 95% travel time in a day is less than 800 seconds and one data's travel time is 2 000 seconds, then this data shall be deleted. Step 2: divide a day into several time intervals with equal length. For data whose time of day belongs to the same time interval, the data whose travel time is too high or too low is deleted. For example, for data whose time of day is between 0 and 1 o'clock, most of their travel time is around 200 seconds. There is one data whose travel time is 600 seconds, and then this data shall be deleted. The cleaned data set gives the scatted chart of travel time–time of day. The average travel time from 0:00 a.m. to 6:00 a.m. is the average

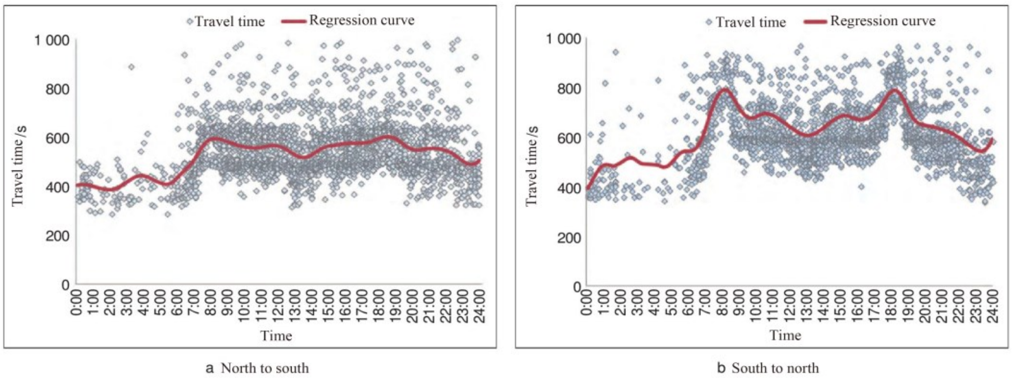


Figure 8 Travel time and time of day relationship at Dongshan Avenue (Gangyao–Wangjiahe Section)

free-flow travel time, and the average free-flow speed can be obtained by dividing the road length by the average free-flow travel time. Based on the travel time peaks and non-peaks, we can obtain the average travel time and speed during peak (non-peak) hours, the peak (non-peak) hours, the length of peak (non-peak) hours, and the maximum and minimum travel time during peak (non-peak) hours. The difference between the largest and smallest travel time at the same time of day is the travel time bandwidth, showing the maximum travel time difference at a certain moment. In addition, we can get other indicators, including the TTI index and the road operating grade (reflecting road congestion levels).

Dongshan Avenue between Gangyao Road and Wangjiahe Road in Yichang City is taken as the study object, which is located at the boundary of the central city. Gangyao Road is in the north, while Wangjiahe Road is in the south. There are multiple intersections on Dongshan Avenue between Gangyao Road and Wangjiahe Road, through which the vehicles may enter and leave Dongshan Avenue. The scatted chart of travel time-time of day in Dongshan Avenue between Gangyao and Wangjiahe is as follows (see Figure 8). In Figure 8(a), the travel time in the early morning (0:00 a.m.–5:00 a.m.) for the north-south direction is around 400 seconds. During the day time (6:00 a.m.–18:00 p.m.), the travel time is between 420–720 seconds, and the travel time bandwidth is 300 seconds. There is no travel time peak during a day, and the TTI index is 1.5. In addition, the daily traffic flows at Gangyao entrance and Wangjiahe exit for the north-south direction are 21,000 pcu and 11,000 pcu, respectively. It indicates that at least 50% of the vehicles that entered the Gangyao entrance did not arrive the Wangjiahe exit but left somewhere in between. With other traffic indicators, we conclude that the traffic volume on Dongshan Avenue from Gangyao Road to Wangjiahe Road is not high and the traffic is not congested. In Figure 8(b), the travel time in the early morning for the south-north direction is around 400 seconds, and there are travel time peaks during a day. The travel time peak is between 750–900 seconds, with a bandwidth of 150 s. The travel time non-peak is about 500–700 seconds, with a bandwidth of 200 seconds. The TTI index for peak hours is 2.0. In addition, the daily traffic flow at the Wangjiahe entrance and Gangyao exit for the south-north direction are 13,000 pcu and 16,000 pcu, respectively. This indicates that a small number of vehicles entered Dongshan Avenue somewhere between Wangjiahe entrance and Gangyao exit. With other traffic indicators, we find that traffic volume on Dongshan Avenue from Wangjiahe Road to Gaoyao Road is low. The travel delay in the morning and evening peak hour hours are high, which means that the south-north direction is in congestion in the morning and evening peak hours.

The road operation conditions of the two directions of Dongshan Avenue between Gangyao Road and Wangjiahe Road are significantly different. Although they are both located at the boundary of the central city, Wangjiahe Road is not an important traffic attraction, so the traffic demand from Gangjiao Road to Wangjiahe Road is not high. Thus the north-south direction is not congested. As an important gateway into the city, the south-north direction has typical morning and evening peaks. The reasons for such differences are closely related to the urban road network and land uses of Yichang City, which are not discussed in this study. In addition, the travel time bandwidth represents the vehicle's stop delays (including signal control delays and delays related to pedestrian crossing). The time bandwidth for both directions are more than 150 seconds and the bandwidth for the north-south direction is more than 400 seconds. Measures should be implemented to reduce the delays, such as setting green waves and constructing footbridges.

In summary, based on the check point sequences and time sequences of vehicles passing a selected road, the travel time and time of day relationship of the selected road can be obtained, and a series of indicators are obtained as an important basis for traffic analysis.

5 Analysis framework of traffic camera data-based road traffic

The check point sequences and time sequences contain the trajectories of all vehicles in the city with valuable road travel patterns. We need effective technical methods to extract them from the data. The three analytical tasks and solution methods described above are just tips of the iceberg. However, traffic camera data mining and urban road traffic analysis are emerging technologies both in academic research and engineering practice without standards.

Through research and practice, this paper summarizes the Bottom to Top(B2T) procedure, which guides the analysis of traffic camera data and other kinds of traffic data. The B2T procedure consists of three steps involving four levels (see Figure 9). Step 1: based on the massive and diverse data, use statistical methods and data mining algorithms to obtain the indicator layer which consists of a vast variety of traffic indicators. Step 2: interpret the traffic indicators with professional knowledge of transportation engineering to obtain urban travel patterns and the information layer, which guide engineering applications. Step 3: extract traffic rules from the information layer. The data layer is the bottom layer of the information pyramid, with the rule layer on the top. Data analysis is the process of extracting valuable information from one layer to obtain the upper layer and finally get the topmost and most valuable layer of the pyramid of information.

Obtaining the indicator layer is the most complicated step. Firstly, the indicator layer is an important medium layer between the data layer and the information layer. The traditional traffic indicators are useful, but data mining algorithms can bring new traffic indicators which show the potential values of data. Secondly, extracting the indicator layer from the data layer to is an open exploration process without traditional and fixed data mining procedures and algorithms. Thirdly, the acquisition of the indicator layer is subject to both data layer and information layer. The new traffic indicators that can be extracted may not have practical values, while the traffic indicators with practical values may not be obtained by existing data mining algorithms. Setting new traffic indicators, developing analytical tasks, designing and testing mining algorithms require trials and iterations. Meanwhile, we need an extendable traffic analysis framework to summarize the trials and lay a foundation for future practical standardization.

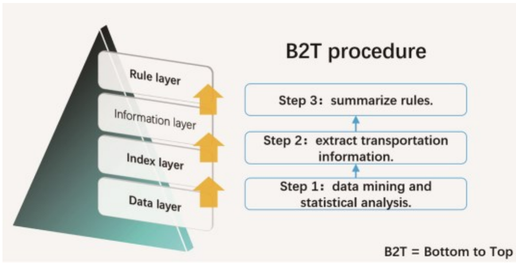


Figure 9 B2T procedure

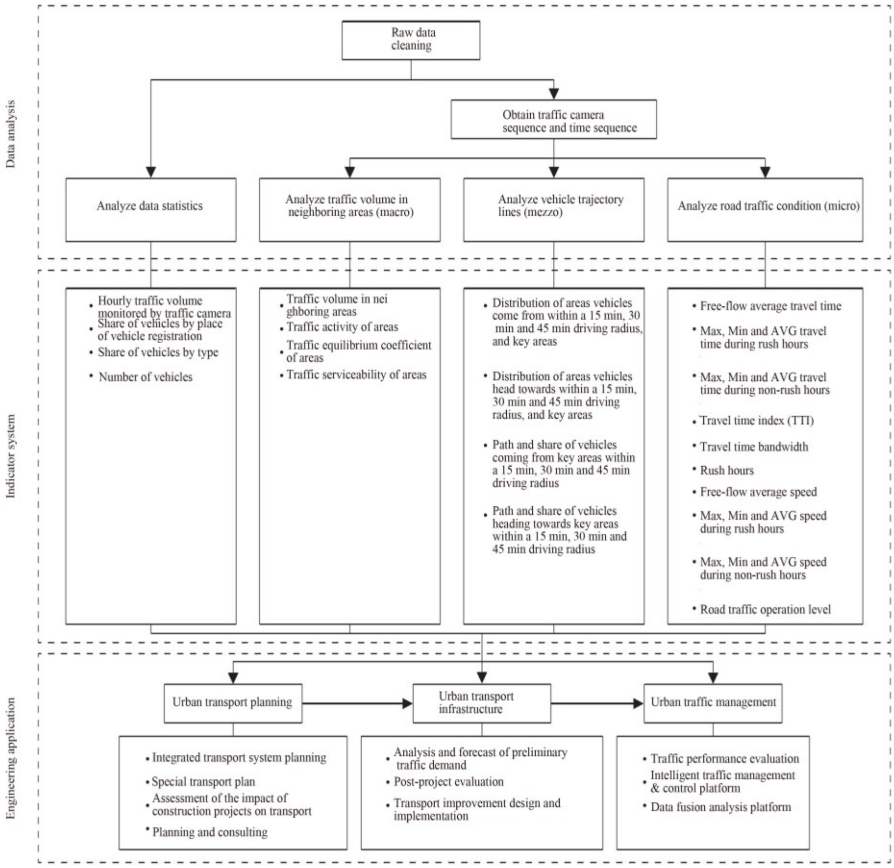


Figure 10 Analysis framework of traffic camera data-based road traffic

This paper proposes a traffic camera data-based road traffic analysis frame. It is divided into three parts: data analysis, indicator hierarchy and engineering application (see Figure 10). Data analysis is a core technology component that includes the analytical tasks (such as the three analytical tasks mentioned above) as well as the statistical methods and data mining algorithms to realize those tasks (which are not discussed in detail). The indicator hierarchy contains traffic indicators obtained from data processing, such as the specific indicators obtained from the three analysis tasks mentioned in this paper. The engineering application is to deeply analyze the traffic phenomena and rules hidden in the indicator layer and guide urban transportation planning, construction, and management. For example, the results of road traffic analysis in the case of Yichang City in this paper can serve as a guide for the construction of urban road traffic in Yichang City. The road traffic analysis frame based on traffic camera data can be expanded with new data analysis, new traffic indicators, and new engineering applications, thus providing a basis for practical standardization of traffic camera data mining and urban road traffic analysis.

6 Conclusions

The traffic camera data analysis can be applied not only to traffic law enforcement but also to urban transportation planning, construction and management. This paper analyzes the inter-area traffic flows, vehicle trajectories and road operation levels. Moreover, it proposes a series of traffic indicators that cannot be obtained by traditional traffic survey methods, such as traffic activity level of an area, inter-area traffic balance coefficient, *m*-min vehicle origin and destination distributions, key routes, the shortest and longest travel time of roads, and time bandwidth of road travel. With the data of Yichang city, Hubei Province, the traffic flow distribution of downtown Yichang, the origins and destinations of vehicles to and from the major check points, and the comparisons of the two-way traffics of city arterials, etc. are presented. The results can be used to guide integrated transportation system planning, specific transportation planning, assessments of effects from traffic construction projects, traffic demand analysis and forecast, and post-traffic assessment of construction projects, traffic improvement design and implementation, traffic transportation assessment and intelligent traffic control platform, etc.

Annotation

① Travel Time Index, TTI is provided in the Highway Capacity Manual for the assessment of traffic congestion, and its formula is peak hour travel time divided by free flow travel time. The larger value indicates the more congested road.

② The camera data is from the Traffic Police Detachment of Yichang Public Security Bureau, Hubei Province, China.

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