Multi-View Actionable Patterns for Managing Traffic Bottleneck

Xiaodong Yue  
School of Computer Eng & Sci  
Shanghai University  
Shanghai, 200444, China

Longbing Cao  
Advanced Analytics Institute  
University of Technology, Sydney  
NSW, 2007, Australia

Yufei Chen  
School of Electronics & Info  
Tongji University  
Shanghai, 201804, China

Bin Xu  
School of Transportation Eng  
Tongji University  
Shanghai, 201804, China

Abstract

Discovering congestion patterns from table-formed traffic reports is critical for traffic bottleneck analysis. However, patterns mined by existing algorithms often do not satisfy user requirements and are not actionable for traffic management. Traffic officers may not pursue the most frequent patterns but expect mining outcomes showing the dependence between congestion and various kinds of road properties for traffic planning. Such multi-view analysis requires to integrate user preferences of data attributes into pattern mining process. To tackle this problem, we propose a multi-view attributes reduction model for discovering the patterns of user interests, in which user views are interpreted as preferred attributes and formulated by attribute orders. Based on the pattern discovery model, a workflow is built for traffic bottleneck analysis, which consists of data preprocessing, preference representation and congestion pattern mining. Our approach is validated on the reports of road conditions from Shanghai, which shows that the resultant multi-view findings are effective for analyzing congestion causes and traffic management.

Introduction

Although knowledge discovery and data mining (KDD) has become an active research area in information technology fields, there is still a big gap between the research deliverables and real business needs (Fayyad, Piatetsky-Shapiro, and Uthurusamy 2003). Often the data-centric patterns mined by many existing KDD algorithms cannot satisfy user expectations and application environments (Cao et al. 2009). To bridge this gap, traditional data mining objective was transferred to actionable knowledge discovery (AKD). AKD aims to find the actionable patterns which are friendly enough for business people to interpret, validate and action (Wang, Jiang, and Tuzhilin 2006; Yang et al. 2007). Different from the traditional patterns of statistical significance, the actionable patterns involve subjective interestingness measures (Chan, Yang, and Shen 2003; Wong, Fu, and Wang 2003) and coincide with particular user preferences (Liu et al. 2000; Tan, Kumar, and Srivastava 2002; Omiecinski 2003). In reality, user preferences of actionable patterns are essentially related to multiple views of data analysis, in which each view is formally represented by a group of data attributes (Lin, Yao, and Zadeh 2002; Chen and Yao 2006). Therefore, AKD methodologies should have the ability to analyze data from multiple views, i.e. the ability to reduce and organize data attributes according to user preferences to generate actionable patterns.

In the field of intelligent transportation (Ma, Zheng, and Wolfson 2013; Yuan, Zheng, and Xie 2012), it is expected to analyze traffic bottlenecks through discovering congestion patterns from traffic reports (Zhang et al. 2011). Most existing works directly apply the techniques of association rule mining on reports to obtain congestion patterns (Barai 2003; Wong and Chung 2007). However, without considering user preferences and requirements, few patterns of only statistical significance are actionable enough to support traffic management. The congestion patterns obtained by traditional mining methods generally consist of the attributes about road construction, such as road width, length and average delay etc. But changing these factors are always difficult because reconstructing roads in modern cities are really high-cost tasks. Thus these patterns are not applicable for traffic improvement.

For outcomes from actionable congestion patterns, traffic management officers expect to study the causes of traffic bottlenecks from different perspectives. First, they hold the views to facilitate traffic planning. The discovered patterns should indicate the relationship between congestion and the road properties that are easy to be improved, such as car/bike separators, bus lanes and region environment. Second, officers hold the views to involve expert experiences into bottleneck analysis. The road properties being considered important for congestion formation should have high priority to emerge in the final patterns. The experts’ experiences are helpful to discover, employ and interpret the actionable patterns. As mentioned above, each view for traffic bottleneck analysis actually denotes a kind of preference of road prop-
Aiming at the problems, we propose a multi-view pattern mining model for traffic bottleneck analysis. Our contributions are summarized as follows.

- **Propose a multi-view attributes reduction model to produce patterns of user interests.** In the model, user views are expressed with attribute preferences and formulated by attribute orders. To implement the order-based attributes reduction, we design a data structure of 2D linked list to store item-discerning elements and set discernibility thresholds to filter out trivial attributes in patterns.

- **Propose a workflow for traffic bottleneck analysis based on the multi-view reduction model.** The workflow consists of data collection & preprocessing of road conditions, user preference representation and attributes reduction for congestion pattern mining. It supports users to analyze the causes of urban traffic bottlenecks from the views of traffic management.

### Multi-view Pattern Mining

#### User View Representation

The views of user in data analysis actually represent the users’ preferences of data attributes. Attributes preferences express various user interests and lead to the multi-view analysis results. The user bias of data attributes can be formally represented in the form of strict order of attributes, i.e. attribute priority.

**Definition 1.** Attribute Order. Given an information system \( IS = (U, C, V, f) \), in which \( U \) is a finite set of data items, \( V \) denotes the domain of attribute values, \( C = \{ a_1, a_2, \ldots, a_m \} \) is the attribute set and \( m = |C| \). A strict attribute order \( S \) on set \( C \) is defined as,

\[
S : a_1 \prec a_2 \prec \ldots \prec a_m
\]

(1)

The order \( S \) is an attribute sequence which defines the priority of attributes, such as \( a_1 \prec a_2 \) denotes the attribute \( a_1 \) is prior to \( a_2 \).

Based on the attribute order, we can further define the order of attribute sets. For an attribute set, the set priority is decided by the priority of its member attributes.

**Definition 2.** Token Attribute. Given an information system \( IS = (U, C, V, f) \), \( S \) is an attribute order on set \( C \). For a subset of attributes \( A \subset C \), a token attribute is the first element of \( S \) contained in \( A \). Obviously, the token attribute owns the highest priority in attribute set \( A \).

**Definition 3.** Attribute Set Order. Given two attribute subsets \( A, B \subset C \), sort the attributes of \( A \) and \( B \) with order \( S \) and obtain \( A^S = \{ a_i, \ldots \} \) and \( B^S = \{ a_j, \ldots \} \), \( a_i, a_j \) are the token attributes of \( A \) and \( B \) respectively. If \( a_i \neq a_j \) and \( a_i \prec a_j \), the sequence \( A^S \prec B^S \) and thus the attribute set \( A \) is prior to \( B \) (\( A \prec B \)); if \( a_i = a_j \), \( A \) and \( B \) have the same priority, i.e. \( A \cong B \).

#### Attributes Reduction for Pattern Mining

Based on the definitions of attribute preference, the user interests can be involved into pattern mining process through attributes reduction. Attributes reduction aims at finding a minimum set of conditional attributes that preserves a certain classification property, i.e. attribute reduct (Pawlak 1991). The attribute reduct with preferences can induce the patterns from different user views. The reduction algorithm is built on the basis of discerning elements. Each discerning element is a set of attributes to distinguish a pair of items belonging to different classes.

**Data Structure** Considering spatial complexity, we use a 2-dimensional list to store the discerning elements. The first-dimension list represents \( M \) conditional attributes of system. On the second dimension, each attribute \( a_i \) has a linked list of discerning elements, in which all the elements have the same token attribute \( a_i \). To further simplify the 2-dimensional list, we use the following strategies to remove redundant discerning elements.

- Because the comparison of two items is symmetric, i.e. the discerning element \( e(i, j) = e(j, i) \), for each item pair, just one copy of their different attributes is stored in the list.

- Reduce redundant discerning elements based on Absorption Law in Set Theory. For two elements \( e \) and \( e' \), if \( e \subseteq e' \), \( e' \) can be replaced by \( e \) in the list.

Moreover, before being inserted into the linked list, the attributes in every discerning element are sorted by the given order. This strategy facilitates the computation of token attributes and the comparison of attributes in further reduction process. To balance computational time and spatial complexity, Absorption Law is applied to only the elements having the same token attribute rather than the total discerning elements to remove redundancy.

**Reduction Algorithm** The attributes reduction algorithm involving attribute preferences is constructed based on the partition of discerning elements. Given an attribute order \( a_1 \prec \ldots \prec a_m \) for a decision system, referring to Definition 3, the binary relation of equal priority \( \cong \) between two attribute sets depends on their token attributes. Obviously, the relation \( \cong \) is reflexive, symmetric and transitive, thus can partition all the discerning elements (attribute subsets) \( M \) into \( m \) disjoint equivalence classes, \( M/ \cong = \{ [a_1], \ldots, [a_m] \} \). Each equivalence class \( [a_i] \) is denoted by the common token attribute and all the elements of it have the same priority. Thus we also have \( [a_1] \prec \ldots \prec [a_m] \).

Through partitioning the discerning elements, item discernibility is graded to different levels according to the predefined attribute preference. Recalling the data structure, the second-dimension lists represent the partition of discerning elements. Based on this, the reduction algorithm with attribute preference is designed as follows.

As shown in Algorithm 1, in reduction process, attributes are selected according to their priority and discernibility. For the attribute with high priority, it takes precedence to distinguish item pairs and thus is more likely to occur in the
Algorithm 1 Reduction with Attribute Preference (RAP)

Input:
Decision system $DS = (U, C \cup D, V, f)$, $|C| = m$,
Attribute preference, $S : a_1 \prec a_2 \prec ... \prec a_m$

Output: Attribute reduct $R$ based on the preference $S$
1. Initialize reduct $R = \emptyset$;
2. Construct the 2-dimensional list $M$ to partition all the
discerning elements. $m$ linked lists represent the equivalence classes of $m$ token attributes, $\{[a_1], ..., [a_m]\}$, and
class priority $[a_1] \prec ... \prec [a_m]$;
3. while $M \neq \emptyset$ do
   4. Choose the class one by one from low to high priority;
   5. for $i = m$ to 1 do
      6. Check the irreplaceable discernibility of $a_i$;
      7. if $|[a_i]| < T_{id}$ then
         8. Delete all the elements of $[a_i]$ from $M$;
      9. else
         10. Browse $M$ forward and count the number of ele-
             ments which contain the attribute $a_i$, the number
             is denoted by $K_{ai}$;
         11. Check the general discernibility of $a_i$;
         12. if $K_{ai} < T_{id}$ then
            13. Delete all the elements of $[a_i]$ from $M$;
         14. else
            15. Add attribute $a_i$ to reduct $R$ and delete all the
                elements containing $a_i$ from $M$;
      16. end if
   17. end if
   18. end for
   19. end while
20. Output attribute reduct $R$.

The attribute reducts including more attributes than the traditional
patterns. Thus it is required to analyze the redundancy of the attribute
reducts with user preferences. Next we prove
that the attribute reducts obtained by the proposed reduction
model are still independent, i.e. all the attributes in a reduct
are necessary for classification (Pawlak 1991). This means
the reducts contain no redundant attributes and guarantee the
high-quality patterns.

Theorem 1. Given a decision system $DS = (U, C \cup
D, V, f)$, $|C| = m$ and an attribute preference $S : a_1 \prec
a_2 \prec ... \prec a_m$, suppose the partition of discerning ele-
ments induced by $S$ is $\{[a_1], ..., [a_m]\}$. For any attributes
$a_p, a_q \in C$, if the attribute priority $a_p \prec a_q$, then $\forall e \in \{a_q\}$,
$e \cap \{a_p\} = \emptyset$.

Proof. For any element $\forall e \in \{a_q\}$, $e$ is a subset of attributes
to discern an item pair and its token attribute is $a_q$. According
to Definition 2, any attribute $a \in e$ cannot be prior to
the attribute $a_q$, $a_q \not\prec a$. Because $a_p \prec a_q$, we have
$a_p \prec a \not\prec a_q$ and $a_p \not\prec a$, the attribute $a_p$ is prior to
any attribute in $e$. Thus for any element $e$ in class $\{a_q\}$, it
does not contain the attribute $a_p$, i.e. $e \cap \{a_p\} = \emptyset$.

As shown in Theorem 1, for a class of discerning ele-
ments, all its members cannot contain the attributes which
are prior to its token attribute. This indicates that if the dis-
cerning class $[a]$ is not empty, the discernibility of attribute
$a$ cannot be replaced by the attributes prior to it. Generally,
the more elements $[a]$ has, the more important attribute $a$ is
for discerning item pairs. Even owning low priority, attribute
$a$ should be selected into reduct due to its irreplaceable dis-
cernibility. Based on Theorem 1, we can further check the
dependency of the reduct attributes.

Theorem 2. Given a decision system $DS = (U, C \cup
D, V, f)$, $|C| = m$ and an attribute preference $S : a_1 \prec
a_2 \prec ... \prec a_m$, the attribute reduct obtained by algorithm
RAP is independent.

Proof. Suppose $R$ is a reduct obtained by algorithm RAP, $R$
consists of $k$ attributes, $R = \{r_1, r_2, ..., r_k\}, r_i \in C, 1 \leq i \leq
k$, and the attribute priority $a_1 \not\prec r_1 \not\prec r_2 \not\prec ... \not\prec r_k \not\prec
a_m$. In order to prove a reduct $R$ is independent, referring to
the definition of attribute reduct (Pawlak 1991), we should
demonstrate that every attribute in reduce $R$ is indispensable.

First we demonstrate attribute $r_k$, which has the lowest
priority in $R$, is indispensable in reduce $R$. Since RAP selects
attributes from low to high priority, $r_k$ is the first selected
attribute and $r_k = \min \text{priority} \{a_i | [a_i] \neq \emptyset\}, \forall r \in R -
\{r_k\}, r \not\prec r_k$. According to Theorem 1, we have $\forall e \in \{r_k\}$,
$e \cap \{r\} = \emptyset$. This means the item pairs discerned by $r_k$
cannot be distinguished by the other attributes in reduct, thus
$r_k$ has irreplaceable discernibility and is indispensable in $R$.

Next we demonstrate the other attributes in $R$ indispensable.
$\forall r \in R - \{r_k\}$, suppose $M'$ be the set of discerning
elements before selecting attribute $r$, referring to RAP al-
gorithm, all the elements containing the reduct attributes of
the priority lower than $r$ have been removed from $M'$, i.e.
$\forall r' : r' \not\prec R \cap \not\prec r', \forall e \in M'; e \cap \{r\} = \emptyset$. Since
$[r] \subset M'$, we have $\forall e \in [r], e \cap \{r\} = \emptyset$. For the reduce
attributes prior to $r$, $\forall r'' : r'' \not\prec R \cap r'' \not\prec r$, according to

Model Analysis

Involving the attributes of user interests may lead to the at-
tribute reducts including more attributes than the traditional
Theorem 1, \( \forall e \in [r], e \cap \{ r^* \} = \emptyset \). As mentioned above, for the reduct attributes whether prior or posterior to \( r \), \( r \) has the irreplaceable discernibility. Thus \( r \) is indispensable in \( R \).

To sum up, all the reduct attributes \( \{ r_1, r_2, \ldots, r_k \} \) are indispensable in \( R \). Thus the reduct obtained by RAP is independent. \( \square \)

From Theorem 1 and 2, we know that adding the attribute preference as prior information to attributes reduction model is helpful to not only discover patterns from user views but also guarantee the patterns without redundancy.

**Workflow of Traffic Bottleneck Analysis**

**Data Preparation**

The target of traffic bottleneck analysis is to study the causes of road congestion. Urban traffic congestion is not only related to road construction, but also city planning and traffic management. In this paper, we adopt 14 attributes as candidate factors for fully analyzing urban traffic congestion, in which some factors are inherent road properties about construction and traffic capacity and the others are related to road programming and region environment. Using attributes reduction model to discover data patterns of traffic congestion, it is necessary to discretize attribute values to obtain a symbolic and semantic description of road properties. The criteria of discretization are made through referring to Urban Road Traffic Performance Index and expert experiences. Table 1 lists the description and discretization criteria of all attributes. Besides the conditional attributes of road properties, the decision attribute value to judge whether a road is a traffic bottleneck is assigned by domain experts.

**User Preferences**

The user preferences of road properties for traffic bottleneck analysis come from either application requirements or domain knowledge. As introduced above, the user preferences of road properties are formulated by attribute orders. Thus we can model the user views of traffic bottleneck analysis through setting the priority of road properties. To facilitate this setting, we divide 14 road properties into 5 groups from the aspects of road construction, infrastructure setup, traffic environment, traffic capacity and bus station. To obtain a total order of properties, users can first rank property groups and then adjust order within each group. This strategy is implemented through a friendly user interface.

For example, if traffic management personnel hold a view to avoid traffic congestion through optimizing road infrastructure setup and traffic environment, the following road property order can be used to express user preference.

- Preference for infrastructure setup and environment:
  - \( \text{Car/bike separator} \prec \text{Middle separator} \prec \text{Zebra strips} \prec \text{Exit/entrance} \prec \{\text{Region} \prec \text{Land type} \prec \text{Traffic volume}\} \prec \{\text{Bus lane} \prec \text{Bus station}\} \prec \{\text{Joint roads number} \prec \text{Capacity difference}\} \prec \{\text{Lane number} \prec \text{Length} \prec \text{Average delay}\} \)

**Extract Patterns of Traffic Bottleneck**

Given a user preference of road properties, we can use attributes reduction model to extract patterns of traffic bottlenecks from the corresponding view. For a decision system of traffic congestion, first RAP algorithm is used to obtain an attribute reduct of road properties with user preference. Next candidate patterns of traffic congestion are generated through integrating attribute values into the reduct. Finally, based on pattern evaluation criteria, the redundant patterns in candidate ones are filtered out. The workflow of discovering traffic bottleneck patterns is shown below.

**Algorithm 2 Extracting Traffic Bottleneck Patterns**

1. Preprocess the data of road conditions;
2. Formulate user preferences with the priority orders of road properties;
3. For a priority order, utilize RAP algorithm to compute an attribute reduct of road properties;
4. For every item of class ‘congestion’, integrate its property values into attribute reduct to form a candidate pattern;
5. Remove redundant patterns and filter out the candidate patterns according to their Confidences and Lifts.

**Example 1.** Suppose users have a preference of infrastructure setup and region environment, the attribute reduct obtained by RAP algorithm consists of the following road properties: Traffic volume, Land type, Region, Zebra strips and Middle separator. For the items of class ‘congestion’, integrate property values to produce candidate patterns as

1. Traffic volume = 1 \( \land \) Land type = 2 \( \land \) Region = 2 \( \land \) Zebra strips = 0 \( \land \) Middle separator = 2 \( \{\text{Conf: 0.714, Lift: 2.187}\} \)
2. Traffic volume = 1 \( \land \) Land type = 4 \( \land \) Region = 3 \( \land \) Zebra strips = 0 \( \land \) Middle separator = 1 \( \{\text{Conf: 1, Lift: 3.061}\} \)

After filtering out the candidate patterns by Confidence and Lift, finally we obtain the patterns of traffic congestion as follows.

1. Traffic volume = 1 \( \land \) Land type = 4 \( \land \) Region = 3 \( \land \) Zebra strips = 0 \( \land \) Middle separator = 1 \( \{\text{Conf: 1, Lift: 3.061}\} \)

The patterns above indicate the coupling effects of separator setting and region environments on traffic congestion. Users can study the dependence between congestion and other road properties through reformulating their preferences.

**Experimental results**

For experiments, we build up a decision system of the road conditions in urban areas of Shanghai. Each record in the decision system has 14 conditional attributes (see Table 1) to present the properties of an urban road and 1 decision attribute to judge congestion. We select 300 representative road sections from thousands of ones to form the experimental data. These road sections cover 9 districts in the urban area of Shanghai, which include Huangpu, Jing’an, Changning, Hongkou, etc. 17% of these road sections locate within the inner-ring city area and 83% locate around the middle-ring. The region types of these road sections involve Entertainment (2.7%), Residential(64.3%), Business(26%)
and Government(7%). The data of road conditions were collected in a period of 12 months thus can reflect the city traffic situation comprehensively.

To validate the capability of our approach for mining actionable traffic patterns, we evaluate patterns from the aspects of accuracy, concision and user interests. The popular measures of Confidence and Lift are used to evaluate pattern accuracy. The pattern concision is measured by the compression ratio of conditional attributes. Finally, the degree-of-interest of a pattern is evaluated by the average of preference scores of all pattern attributes. The preference scores of attributes are determined by priority order. The ith attribute can be simply assigned the score |C| − i + 1. The higher priority an attribute has, the higher score it is assigned. We present an overall evaluation of RAP patterns through comparing with the following popular pattern mining algorithms: Apriori (Han, Kamber, and Pei 2011), Predictive Apriori (Scheffer 2001) and Tertius (Flach and Lachiche 1999). Suppose a user holds the preference for road infrastructure setup and environment, Table 2 lists the best 3 congestion patterns generated by different pattern mining methods.

As shown in Table 2, RAP can extract the precise congestion patterns with high Confidences and Lifts as most existing methods. Focusing on the co-occurrence of items, the patterns mined by the traditional algorithms always consist of the attributes of road construction. From the patterns, we find that the roads of long length and high average delay are more likely to be congested. But in a modern city, it is difficult to change these road conditions directly. Thus these patterns are not actionable to support traffic planning. For the traffic officers who are interested in the roles of separator setting and region environment in traffic congestion, these patterns cannot coincide with his expectation. Through involving attribute preferences into pattern mining, RAP captures the correlation between congestion and the road properties of user interests. RAP patterns indicate the effects of separator setting and region environment on congestion. In the business and residential regions within the middle-ring city area, the deficiency of road separator setting easily leads to traffic block even if the surrounding traffic volume is normal. Meanwhile, in the central city area of high traffic volume, the effective way to ease the traffic congestion is crowd decentralization. Moreover, capturing comprehensive correlation among road properties, RAP patterns generally contain more attributes than frequent patterns. But it should be noticed that no attribute in RAP pattern is redundant, because the attributes reduct obtained by RAP is independent (See Theorem 2).

To further validate the ability of RAP for multi-view actionable pattern mining, we suppose 4 users with different views for traffic bottleneck analysis. These views focus on infrastructure setup, bus station, traffic capacity and road construction respectively. Figure 1 illustrates the average degree-of-interest of the patterns obtained by different pattern mining methods. Obviously, without considering user interests, traditional algorithms generate the same patterns for different users and thus result in low degree-of-interest. Especially for the users being interested in the road properties not occurring frequently in the congestion records, such as bus lane, traditional algorithms over focus on road construction and cannot provide the satisfactory results. We also find that when the user has an attribute preference for road construction, the degree-of-interest of the traditional patterns will be close to RAP patterns. This indicates that adopting the specific attribute preferences, RAP can obtain

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the patterns similar to the traditional ones. For the users with different interests of patterns, RAP actually provides a flexible tool for data analysis.

As an inductive learning tool, attributes reduction targets at reducing original attributes to an attribute reduce while preserving the classification property of system (Pawlak 1991; Lin, Yao, and Zadeh 2002). To involve prior information into attributes reduction, Wang first designed a reduction algorithm based on attribute orders and analyzed its properties. The reduction process is built up on the basis of discernibility matrix (2001). Yao proposed a formal framework to represent the attribute bias by both qualitative and quantitative judgements for machine learning (2008). Zhao also utilized attribute orders to find a particular reduce according to user interests. The quality of the output reduce relies on the free attributes selected in reduction process (2002). Han and Wang further analyzed the relationship between attribute orders and reducts to judge whether similar attribute orders produce the same reduce (2005).

**Conclusion**

How to make the outcomes from traffic data mining actionable for traffic bottleneck diagnosis and management is a challenging task. The challenge lies in the gap between diversified user requirements and classic data-driven methodologies. This paper proposes attributes reduction model for extracting actionable traffic congestion patterns that present multiple views of business and cater for traffic manager’s interests. User views are expressed by attribute preferences, which are formally represented by attribute orders. We validate our approach based on the reports of road conditions from Shanghai. Experimental results show that the proposed approach is effective in analyzing congestion causes from the views of traffic management.

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