Urban Traffic Bottleneck Identification Based on Congestion Propagation

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***Abstract*—Traffic congestion has seriously caused various problems in society, economy and environment, especially in urban areas. A traffic bottleneck is always seen as the root cause of congestion which frequently deduces the congestion emergence, queues formation and congestion propagation. However, bottlenecks are caused by many complicated factors and vary with spatial and temporal environment which are difficult to be defined and identified in urban areas. In this paper, we first propose a novel definition of bottlenecks in urban area based on the congestion propagation costs and the congestion weights of road segments. Then according to the definition, we present an urban bottleneck identification method using causal congestion trees and causal congestion graphs to identify some bottlenecks. This paper implements some experiments based on the urban inductive loop detector data. According to our proposed method, we identify several bottleneck groups around the urban area. Furthermore, we also improve the road capacity of identified bottlenecks and compare the congestion level and congestion propagation range before and after the improvement to verify the identified bottlenecks.**

***Index Terms*—Bottleneck identification, congestion propagation, urban traffic network, graph theory.**

I. Introduction

Traffic congestion is considered as one of the most important issues in many cities over the world, which reduces the utilization of the transportation infrastructure and increases travel time, air pollution and fuel consumption. According to a recent urban transportation scorecard [1], in the 471 U.S. urban areas, the congestion "invoice" for the cost of extra time and fuel was estimated as \$160 billion in 2014, which is expected to reach \$192 billion in 2020. In addition, congestion wasted 6.9 billion hours of extra time and 3.1 billion gallons of fuel in 2014 [1]. Therefore, traffic congestion has caused serious problems in society, environment and economy, especially in urban areas.

Traffic bottleneck is often regarded as the root cause of congestion on freeways or urban roads and is a spatial discontinuity where road capacity is reduced [2][3]. A bottleneck may generate a queue of vehicles and frequently propagate to the neighbor road segments, which leads to consequently extra travel delay, congestion chain, and worse traffic efficiency and safety. Therefore, identifying the position of bottlenecks is important for the advanced traffic management system (ATMS) in the intelligent transportation system (ITS) to make the proper plans improve the performance of road network.

Bottleneck is caused by many complicated factors and is very difficult to be defined and identified, especially in urban traffic network because of the extremely complicated travel behavior and road network topology. On freeways, there are less traffic signals and intersections and the bottleneck is typically static and located near on- and off- ramps. In this way, most of previous studies in freeway bottleneck identification evaluate the flow, speed or travel time gap between road upstream and downstream which is seen as a bottleneck of the road segment [4][5]. However, the identification of traffic bottleneck in urban area is more difficult than that on freeways, because of road topology complexity and traffic factors. X. Ye et al. [9] provided a congestion propagation model of urban network traffic based on route choice model. They used a critical threshold to indicate whether a link is a bottleneck or not. However, the threshold is more likely to identify whether a road segment is congested or not and cannot identify the bottlenecks in urban traffic network efficiently. In [10], authors analyzed the bottleneck in urban expressway based on detector data. They regarded the place where congestion first occurred as a bottleneck. However, this method cannot work in the urban area where congestion may occur in several road segments simultaneously, thus it is difficult to identify the specified bottlenecks in the urban traffic network.

Therefore, in this paper, we define the bottlenecks in urban traffic network as the most significant road segments in urban area and the significance means the road segments will lead to more congestion cost in urban area. Based on the definition, our proposed bottleneck identification methodology comprises of three steps: 1) we define the congestion correlation [2][6] between road segments and obtain the congestion correlations; 2) we propose an algorithm to construct the causal congestion trees (CCTs) according to the congestion correlations and record all edges in trees with the same root together to build causal congestion graphs (CCGs); 3) we calculate the costs of all road segments in urban area according to the congestion propagation path in the obtained graphs and get the average costs of all road segments in all graphs to identify some bottlenecks in urban area. In addition, we also verify the identified bottlenecks according to the detector data in Kaohsiung, which evaluates the congestion level and congestion propagation range before and after increasing the capacity of each bottleneck.

To the best of our knowledge, there were very few studies that explicitly define, identify and verify the traffic bottlenecks

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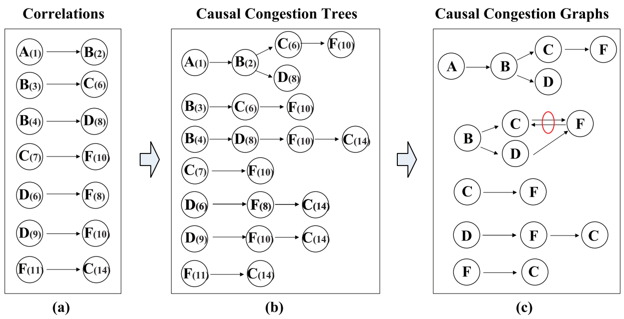

Fig. 1: Process of constructing causal congestion trees and causal congestion graphs

in urban areas. We emphasize that our proposed methodology differs from any other we are aware of, which can identify bottlenecks in urban area based on the average congestion costs of road segments. The contributions of this paper are listed as follows.

- We propose a novel congestion correlation definition, which better captures the spatio-temporal causal relationships between congestion on road segments.
- We propose a bottleneck definition in urban traffic network according to their congestion costs using CCTs and CCGs. To the best of our knowledge, this is the first paper that defines and identifies bottlenecks in urban traffic network according to congestion costs of road segments, which can quantify the costs of congestion on each road segments to congestion in the whole urban area rigorously.
- We improve the road capacity of each identified bottleneck and compare the the congestion level and congestion propagation range before and after the improvement, which can verify the effectiveness of our proposed bottleneck identification methodology.

The rest of paper is organized as follows. The context in Section II develops a method to identify traffic bottlenecks in urban traffic network based on the CCTs and CCGs. Some experiment results and discussion are presented in Section III based on the detector data in Kaohsiung. Section IV offers the concluding remarks and future works.

II. Methodology

A. Congestion Correlation

In order to get the correlations between the congestion on two road segments, we need to get the definition of congestion in urban areas. In [11] and [12], authors provide a definition that if the average speed of vehicles in a road is less than 20 km/h in metropolitan area, this road can be seen as congested. Based on this, most of the existing definition about congestion correlation between road segments is composed of two aspects: 1) congestion on road segments occurs in sequence; 2) road segments are connected spatially or the distance between them is within a certain range [6][7]. However, this definition neglects congestion contingency on road segments. That is to say, if the congestion correlation between road segments just occurs a few times in a long duration because of traffic incidents and according to the existing congestion correlation definition, we will take this correlation into consideration. However, it will lead to some unexpected congestion correlations and bottleneck identification errors. Moreover, all the existing researches about the definition of congestion correlation do not consider the congestion propagation speed. For example, if road segment A is in congestion at 7:00 a.m., road segment B is in congestion at 7:05 a.m. and the shortest path distance between them is more than 10 kilometers (under the spatial threshold), thus according to the existing definition, the congestion of them are correlated, however, which is unfounded intuitively. Therefore, in this paper, according to this, we first propose a novel definition about congestion correlation.

Definition 1. *(Congestion correlation between road segments): A congestion correlation between road segment A and road segment B occurs if the following requirements are satisfied.*

- *Spatial threshold or temporal threshold: the shortest path distance or time lag between congestion on road segment A and road segment B is less than spatial threshold T_s or temporal threshold T_t.*
- *Congestion occurrence probability threshold and propagation probability threshold: congestion occurrence probability of road segment A, $P(A = 1)$ should be larger than the congestion occurrence probability threshold T_o. Moreover, we set the state of road segment A as 1 if road segment A is congested, and conversely, the state of road segment A is set as 0. In this way, the congestion propagation probability from road segment A to road segment B (road segment A is congested and the congestion occurs at road segment B in a duration), $P(B = 1|A = 1)$ should be greater than congestion propagation probabilities threshold T_p.*
- *Congestion propagation speed threshold: according to the shortest path distance and congestion time lag between road segment A and road segment B, the congestion propagation speed between the two road segments should be in congestion propagation speed threshold T_{sp}.*

B. Causal Congestion Tree and Causal Congestion Graph

According to the congestion correlation definition above, we can obtain a set of congestion correlations between road segments. In this subsection, we propose a method to construct continuous-time spatio-temporal CCTs and CCGs, which indicates the congestion propagation process from a certain road segment to other road segments in urban area. The methodology is composed of three steps:

- We first choose each congestion correlation as the first single segment of a tree. Then we propose an algorithm to construct continuous-time spatio-temporal causal congestion trees, as shown in Algorithm 1.
- Based on the obtained trees, we gather all the trees with the same root and connect all the edges in these trees together as a directed graph. Thus we can get a set of

directed graphs and there is only the root in a directed graph that the indegree of the vertex is 0. In this way, all the vertexes in a graph can be seen as the causal road segments of the congestion on the root road segment.
- In the directed graph, there might be some bidirectional edges in a graph. However, the congestion propagation direction of each edge with the same root in the graph is often unidirectional. Thus we choose the direction which occurs more frequently in these trees and delete another directed edge in the graph.

Algorithm 1 Constructing continuous-time spatio-temporal causal congestion trees

Input: a set of congestion correlations between road segments with the corresponding congestion time.
Output: a set of continuous-time spatio-temporal causal congestion trees.

for Each $correlation_i$ $(i \in (1, ..., N))$ **do**
  $Trees \leftarrow$ an empty set;
  $Trees \leftarrow Trees \bigcup$ FINDCHILDREN($correlation_i$);
  return $Trees$;
end for

function FINDCHILDREN($correlation_i$)
  if $child.time$ in $correlation_i$ is the last minute in sampling data **then**
    return $correlation_i$;
  end if
  $correlation_i.subnodes \leftarrow$ an empty set;
  for Each $correlation_u$ $(u \in (i+1, ..., N))$ **do**
    if $Trees$ contains $correlation_u.child$ **then**
      continue;
    end if
    if ($correlation_i.child$ == $correlation_u.parent$) **then**
      $correlation_i.subnodes \leftarrow correlation_i.subnodes \bigcup$ FINDCHILDREN($correlation_u$);
    end if
  end for
  return $correlation_i$
end function

An example in Figure 1 is presented to demonstrate the process of constructing continuous-time spatio-temporal causal congestion trees and graphs. According to Definition. 1, we can get a set of congestion correlations, as shown in Figure 1(a). There are two road segments with the corresponding congestion time in each congestion correlation. Then we choose each correlation in Figure 1(a) respectively as the first single segment of a tree and construct the CCTs according to their spatio-temporal relationships based on Algorithm 1. In this way, we can get the corresponding seven trees in Figure 1(b), which indicates the congestion propagation process among the road segments. After that, we gather all the trees with the same root together and build the CCGs. As shown in Figure 1(b), both the second and third congestion propagation trees start from road segment B and both the fifth and sixth congestion propagation trees start from road segment D. Thus we combine the trees with the same root into a graph, as shown in the second and forth graphs of Figure 1(c). Especially, in the second graph starting from road segment B, congestion on road segment C can propagate to road segment F and congestion on road segment F can also propagate to road segment C. Thus in this way, we need to compare the propagation probabilities of road segment C to F and road segment F to C among all the trees with root road segment B and delete the directed edge with lower probability to finish the construction of the CCGs.

C. Bottleneck Identification

Bottleneck is regards as the root cause of congestion in urban traffic network, which is one of the most important limiting factors in terms of road capacity, travel speed and travel time of vehicles. Moreover, how to define the bottlenecks rigorously is the prerequisite of bottleneck identification in urban area. In this subsection, we first propose a definition according to congestion propagation, and then we identify some bottlenecks in urban area based on the definition.

Definition 2. *(Bottlenecks in urban traffic network): the most significant road segments in urban area. The significance means the road segments will lead to more congestion cost in urban area. The cost of a road segment is the sum of two parts: congestion propagation cost (the cost that the congestion on this road leads to the congestion on other road segments) and its own weight.*

According to the average congestion time of all the road segments in a day, we can get the normalized weights of the k road segments, $\overrightarrow{W} = [W_1, W_2, \cdots, W_k]$. Moreover, let y_{ij} be the congestion propagation cost from road segment i to road segment j. In this way, y_{ij} can be presented as

$$y_{ij} = p_{ij} W_j, \tag{1}$$

where p_{ij} is the congestion propagation probability from road segment i to road segment j.

Let Y_i be the congestion propagation cost of road segment i, so Y_i is

$$Y_i = \sum_{r=1}^{R} y_{ij} = \sum_{r=1}^{R} p_{ij} W_j, \tag{2}$$

where R is number of leaves of vertex road segment i. Thus the cost of road segment i is

$$cost_i = W_i + Y_i. \tag{3}$$

We take the graphs in Figure 2 as an example. The original graph is shown in Figure 2(a) and there is only the road segment A in a directed graph that the indegree of the vertex is 0. The congestion on road segment A propagates to road segment B, C, D, E and F along the directed graph. In order to calculate the cost of all the road segments in a graph, we first find the vertexes in a graph whose outdegrees are 0, such

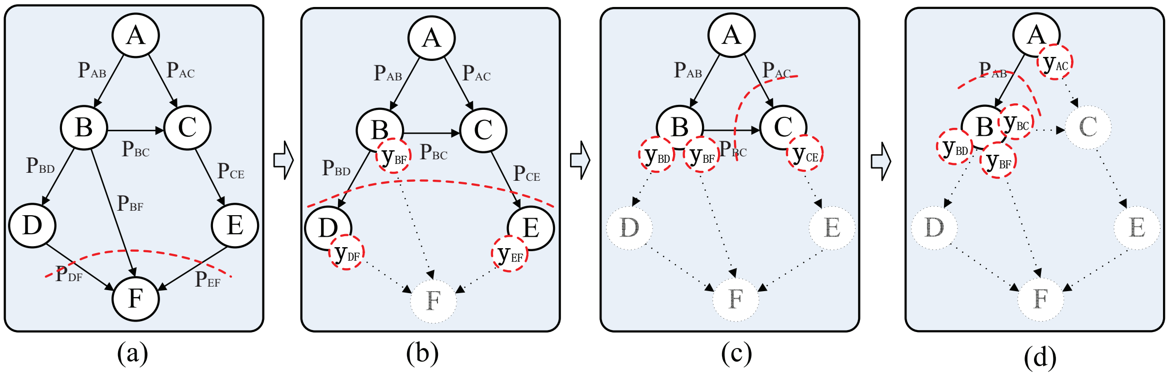

Fig. 2: Calculating the costs of each road segment in a graph

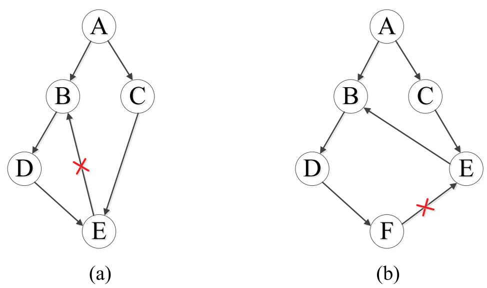

Fig. 3: Cycle in a graph

as the road segment F in Figure 2(a). Then we calculate the congestion propagation cost from the parents of road segment F (road segment B, D and E) to road segment F, y_{BF},y_{DF} and y_{EF} according to Equation 1. After that, we delete the road segment F and the edges from the parents of road segment F to road segment F in Figure 2(a), and obtains the Figure 2(b). Thus the costs of road segment D and E are $W_D + y_{DF}$ and $W_E + y_{EF}$,respectively. Because the road segment C and D are still the children of road segment B, the cost of road segment B will be calculated when all the children of road segment B are deleted from the graph, as shown in Figure 2(d). In this way, we continue to find the vertexes in the graph whose outdegrees are 0 and calculate the costs of all the removed vertexes in the graph until obtaining the cost of the vertex whose indegree is 0 (road segment A).

However, when we calculate the costs of road segments in sequence, if there is a cycle in a graph, we cannot find the vertex in the graph whose outdegree is 0, as shown in Figure 3. In this way, we need to delete an edge in the graph and the edge should satisfy two conditions:

- After deleting the edge, the cycle should be removed. In other words, there should be at least one vertex in a graph whose outdegree is 0.
- After deleting the edge, there should be only one vertex in a graph whose indegree is 0.

Therefore, as the Figure 3 shows, we should delete the edge $E \to B$ in Figure 3(a) and edge $F \to E$ Figure 3(b). In this way, we can remove the cycles in a graph and calculate the costs of all the road segments.

When we get the costs of all road segments in all graphs, we can calculate the average costs of all the road segments and we choose the road segments with high cost as the bottlenecks in urban area.

III. Experiments and Discussion

In this section, we carry out experiments on road network of Kaohsiung, Taiwan and then analyze the performance of our proposed models and algorithm.

A. Data

The proposed congestion propagation model and algorithm are tested based on traffic data generated by the road detectors in Kaohsiung, Taiwan. There are 130 inductive loop detectors in the urban area of Kaohsiung.

Data were collected from 1 April, 2013 to 10 April, 2013 and the sampling interval is 1 minute for a 24-hour period. Because of the missing data in the existing data, we choose the data from 17:00 to 22:00 every day to analyze the congestion propagation and bottlenecks. The data at the first 7 days are regarded as training data to get the proposed model parameters and the data at the last 3 days are used to test the verification of the proposed models and algorithm.

B. Parameter Estimation

Because of the congestion propagation speed threshold T_{sp}, the spatial threshold T_s and temporal threshold T_t can transform each other, and in this paper, we choose temporal threshold T_t as the first item in the definition. In this way, based on the training data, we need to estimate some parameters of our proposed congestion correlation definition. According to Definition 1, four parameters, T_t, T_o, T_p and T_{sp}, need to be estimated. First we determine the temporal threshold T_t based on the detector data and road network in Kaohsiung. Then according to the temporal threshold T_t, we can get a set of preliminary congestion correlations. Moreover, we calculate the congestion occurrence probability on each road segment and congestion propagation probability of the preliminary congestion correlations. Based on these correlations, the frequencies of congestion occurrence probability, congestion propagation probability and congestion propagation speed can be obtained. In this way, we can ensure the parameters T_o, T_p and T_{sp}.

- Temporal threshold T_t: the existing papers about congestion correlations are based on spatial threshold T_s and

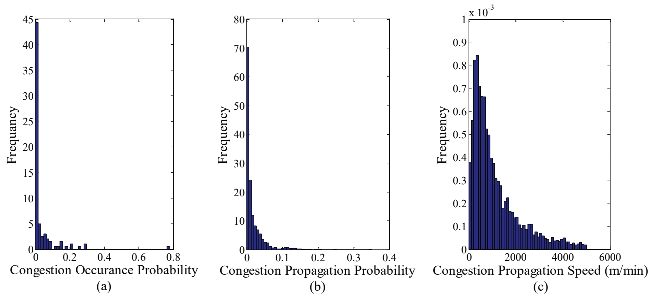

Fig. 4: Congestion occurrence probability, congestion propagation probability and congestion propagation speed frequency

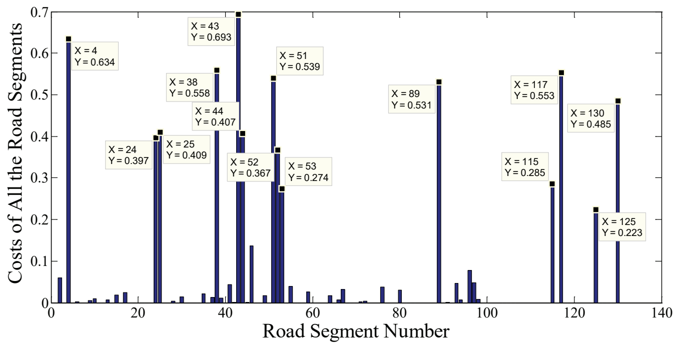

Fig. 5: Average costs of all the road segments

temporal threshold T_t [6][7]. In this paper, because of our proposed congestion propagation speed threshold T_{sp}, we only need to get the temporal threshold T_t. According to the existing detector data and road network in Kaohsiung, we choose 15 minutes as the temporal threshold.

- Congestion occurrence probability threshold T_o and congestion propagation probability threshold T_p: in order to get rid of the occasional congestion correlations, in this paper, we can get the frequencies of congestion occurrence probability and congestion propagation probability from the preliminary correlations according to the first item of the definition, as shown in Figure 4(a) and Figure 4(b), respectively. Then we choose a 80% confidence interval for congestion occurrence probability threshold T_o and congestion propagation probability threshold T_p, respectively, where the area in left tail is 20%.
- Congestion propagation speed threshold T_{sp}: according to the preliminary correlations based on the first item of the definition, we can also get the congestion snapshots of each congestion and the shortest path distance between the correlated detectors. So we can calculate the congestion propagation speeds of all the congestion correlations and get the speed frequency, as shown in Figure 4(c). In this paper, according to the actual congestion propagation speed in urban area, we choose a 60% confidence interval for the congestion propagation speed threshold, where the area in left tail is 15% and the area in right tail is 25%.

C. *Experiment*

1) Experiment on bottleneck identification: In this subsection, we first calculate the average costs of all the 130 detectors, which is shown in Figure 5. Taken the geographic locations of all the detectors and the corresponding costs into consideration, we can divide the detectors into 5 groups: {4, 38, 44, 89, 117}, {43}, {24, 25, 51, 130}, {52, 53, 115, 125} and other detectors, as shown in Figure 6. The road segments whose costs are 0 means that the congestion weights of these road segments are 0 or the congestion on other road segments do not propagate to these road segments. The detectors in first four groups are seen as the bottlenecks in Kaohsiung. The detectors in first group are located in the south of Kaohsiung and most of them are located along the road which is marked in red in Figure 6. The detectors in the third and fourth group are located in the center and north area of Kaohsiung, respectively. However, the second group, detector 43, is different from other groups. Although congestion level of the road segment is less than the other groups, no matter from north area to south area or from south area to north area, most of CCTs will propagate through this location. Thus the second group, detector 43, is also regarded as a bottleneck in the urban area of Kaohsiung.

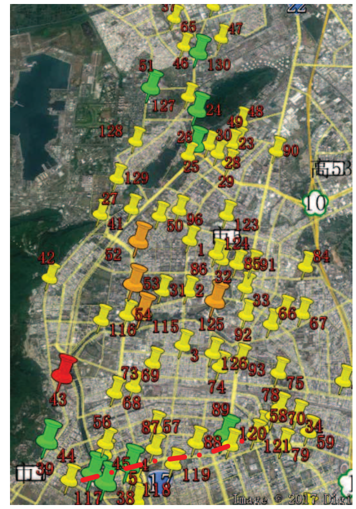

Fig. 6: Identified bottlenecks in Kaohsiung

2) Experiment on identified bottleneck verification: In order to verify the accuracy of our identified bottlenecks, we increase the road capacity of each identified bottleneck and 5 non-bottleneck road segments respectively (we assume that congestion will not occur on the road segments whose capacity is increasing) and record the corresponding average costs of all the road segments whose costs are larger than 0, average number of road segment in a CCG and average congestion duration of a CCT. Then we compare the results among the actual inductive loop detector data without road capacity increasing, average outcomes of each the bottleneck group and average outcomes of non-bottleneck group. The results are shown in Figure 7.

We can see that in Figure 7(a), after increasing the road capacity, the average costs of all the groups decrease and the average costs of the bottleneck groups decrease more than that of non-bottleneck group. Especially, bottlenecks group 1, {4, 38, 44, 89, 117} and bottlenecks group 2, {43} decrease 14.3% and 13%, respective. The result indicates that after increasing

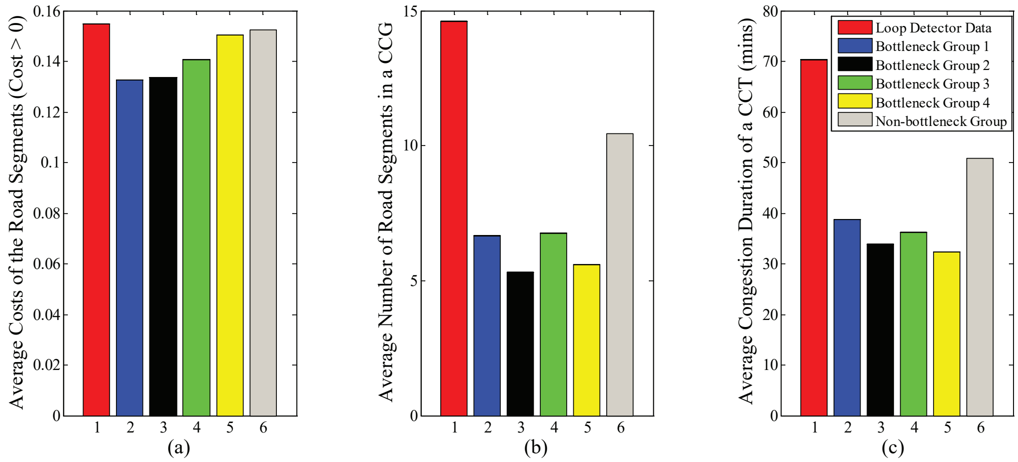

Fig. 7: Bottlenecks identification experiment results

the capacity of bottlenecks, the congestion level will decrease in the whole urban area. The average number of road segment in a CCG and average congestion duration of a CCT are shown in Figure 7(b) and Figure 7(c), respectively. We can see that after increasing the capacity of each bottleneck, the average number of road segment in a CCG and average congestion duration of a CCT decrease about 50%. Especially, the cost of road segments and congestion duration of bottleneck groups 2, $\{43\}$ and bottleneck groups 4, $\{52, 53, 115, 125\}$ decrease more than that of other groups. Because most of CCTs will propagate through road segment 43 and road segment 52, 53, 115 and 125 are located in the central area of Kaohsiung. Thus increasing the capacity of them, the congestion propagation duration and range will decrease significantly.

IV. Conclusion

In this paper, the bottleneck identification in urban traffic network is investigated. First we propose a novel definition of congestion correlations. Then according to this definition, we implement a continuous-time spatio-temporal causal congestion trees algorithm, and then build the CCTs and CCGs, which obtain the congestion propagation paths in urban traffic network. After that, based on our proposed bottleneck definition in urban area, we calculate the average costs of all the road segments and identify several bottlenecks in Kaohsiung urban area. Finally, we improve the capacity of identified bottlenecks and compare the average costs of road segments, average number of road segment in a CCG and average congestion duration of a CCT before and after increasing the capacity of each bottleneck based on the detector data.

However, after identifying the bottlenecks, we cannot identify the most significant bottleneck in each bottleneck group according to their congestion level and congestion costs. Thus in our future work, we will utilize theoretical model to analyze the congestion propagation between the identified bottlenecks and identify the most significant bottleneck in each bottleneck group.

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