A MACHINE LEARNING MODEL FOR BYPASS OPTIMIZATION

Simon Wong

College of Professional and Continuing Education, The Hong Kong Polytechnic University, Hong Kong

ABSTRACT

One performance pledge by Hong Kong Government is to respond to an emergency call within several minutes from the time of call to the arrival of a road transport for emergency services (e.g., an ambulance, a fire vehicle, and a police car) at an incident location. In this regard, ensuring the efficiency of a road transport routing by planning the fastest path for emergency services is important for this performance pledge in Hong Kong. A major obstacle to this performance pledge is frequent unanticipated occurrence of traffic congestion on the planned fastest path in some Hong Kong roads while the design of many of these roads is not feasible for air or sea transport. Detouring is unavoidable when traffic congestion is encountered. To ensure a time-effective detour, backup routes for the detour from the planned path (or simply, bypasses) should be set up beforehand. This paper presents the design of a machine learning model for constructing the optimal bypass structure on top of the planned fastest path from a source to a destination for a road transport for emergency services in Hong Kong. In doing so, Internet of things are installed at each block of a road in heavy traffic-congested areas in Hong Kong for sensing the transit time of each vehicle passing through the block. These large amounts of transit time formulate a big training data set for machine learning to generate a probabilistic model of traffic congestion.

KEYWORDS

Bypass Optimization Algorithm, Machine Learning, Traffic Detour

1. INTRODUCTION

When receiving an emergency call, a source nearest to the incident location (e.g., the nearest fire or police station) sets out transportation towards the incident location. A performance pledge by Hong Kong Government to respond to an emergency call within several minutes (e.g., 12 minutes) from the time when the emergency call is received to the arrival time of a road transport for emergency services at the incident location. To ensure this performance pledge, the fastest (or, the shortest) path from the source to the destination (i.e., the incident location) for the road transport for emergency services is planned. The set-up of the fastest path is affected by many factors such as the local population density, the possible traffic condition affecting by time of the day, and geographic condition of the roads. Despite these factors, once road conditions including the amounts of vehicle transit time are known, Djikstra's algorithm [1] can be adopted to set up the fastest path between the source and the destination for a road transport. As traffic congestion always occurs in Hong Kong roads, especially in heavy traffic-congested areas, the road transport for emergency services must detour from the congested planned fastest path to ensure the performance pledge. In this light, on top of the planned fastest path from the source to the incident location for the road transport for emergency services, backup routes for the detour from

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the planned path (or simply, bypasses) be set up beforehand to save time for searching for time-effective detours due to frequent unanticipated traffic congestion in Hong Kong road conditions.

In this study, a machine learning model for bypass optimization algorithm is proposed to construct the optimal bypass structure along a planned path. For this model to work, Internet of things (IoTs) are proposed to be installed at each block of a road in Hong Kong. These IoTs are used to sense the transit time of each vehicle passing through the block. These large amounts of transit time formulate a big training data set for machine learning to generate a probabilistic model of traffic congestion. Then, the proposed optimization algorithm utilizes binary classification in machine learning to analyze the big data of vehicle transit time at each block along the road and classify the data into either no traffic congestion case or traffic congestion case. Based on these cases, logistic regression classification algorithm can be performed to determine the probability of traffic congestion at each block along the road. To avoid the likelihood of traffic congestion, this probabilistic model can be used by the bypass optimization algorithm to build the optimal bypasses.

2. Research Objective and Significance

Having all the above-mentioned issues in mind, this study is proposed to design a machine learning model to generate a probabilistic model of traffic congestion at some roads in heavy traffic-congested areas in Hong Kong. Then, the bypass optimization algorithm can be designed to adopt this machine learning model to construct the optimal bypass structure for a road transport for emergency services to detour for traffic congestion avoidance and efficient detouring.

The significance of the proposed study is twofold. First, to the best of the proposer’s knowledge, at the time of writing this article, no previous research studies thoroughly explored the machine learning model and the bypass optimization for road traffic detours for emergency services. Second, the proposed bypass optimization algorithm adopts a new probabilistic model based on traffic congestion classifications. As traffic congestions are likely to occur in Hong Kong roads, especially in traffic-busy areas such as Causeway Bay, Central, Mongkok, and Tsim Sha Tsui, this new probabilistic model based on traffic congestion conditions, instead of the probabilistic models based on the occurrence of disasters used in some previous studies (e.g., [2–4]), is more appropriate for this study on Hong Kong road networks.

3. Literature Review

Having all the above-mentioned issues in mind, this study is proposed to design a machine learning model to generate a probabilistic model of traffic congestion at some roads in heavy traffic-congested areas in Hong Kong. Then, the bypass optimization algorithm can be designed to adopt this machine learning model to construct the optimal bypass structure for a road transport for emergency services to detour for traffic congestion avoidance and efficient detouring.

Inspired by the problem of frequent occurrence of traffic congestion in Hong Kong, this study proposes the machine learning model for bypass optimization algorithm to construct optimal bypasses for detours from the planned path for a road transport for emergency services to save time for searching for detours when encountering traffic congestion in Hong Kong. To understand how the optimal bypasses were examined in literature, literature review was performed.

For the literature review, the following inclusion criteria were used to search through some search engines (e.g., Google, ProQuest, Scopus and Web of Science):

- studies published up to the year 2025 when this article was prepared.
- studies related to the shortest or fastest path with bypasses for a road transport for efficient routing.

No results were returned. Then, less stringent search terms were used until some results were found with the following search string in Scopus as an example:

TITLE-ABS-KEY ("shortest path" OR "fastest path" AND "road transport")

This indicates that the previous studies focused on the shortest or fastest path for road transportation instead of bypasses. For example, the studies [5–8] investigated how to set up the fastest or shortest path instead of bypasses.

4. Machine Learning Model for Bypass Optimization Algorithm

For designing the machine learning model for bypass optimization algorithm, a block, which is a portion of a road between two junctions, is considered. For example, Figure 1 shows a block along Lockhart Road between junction A and junction B.

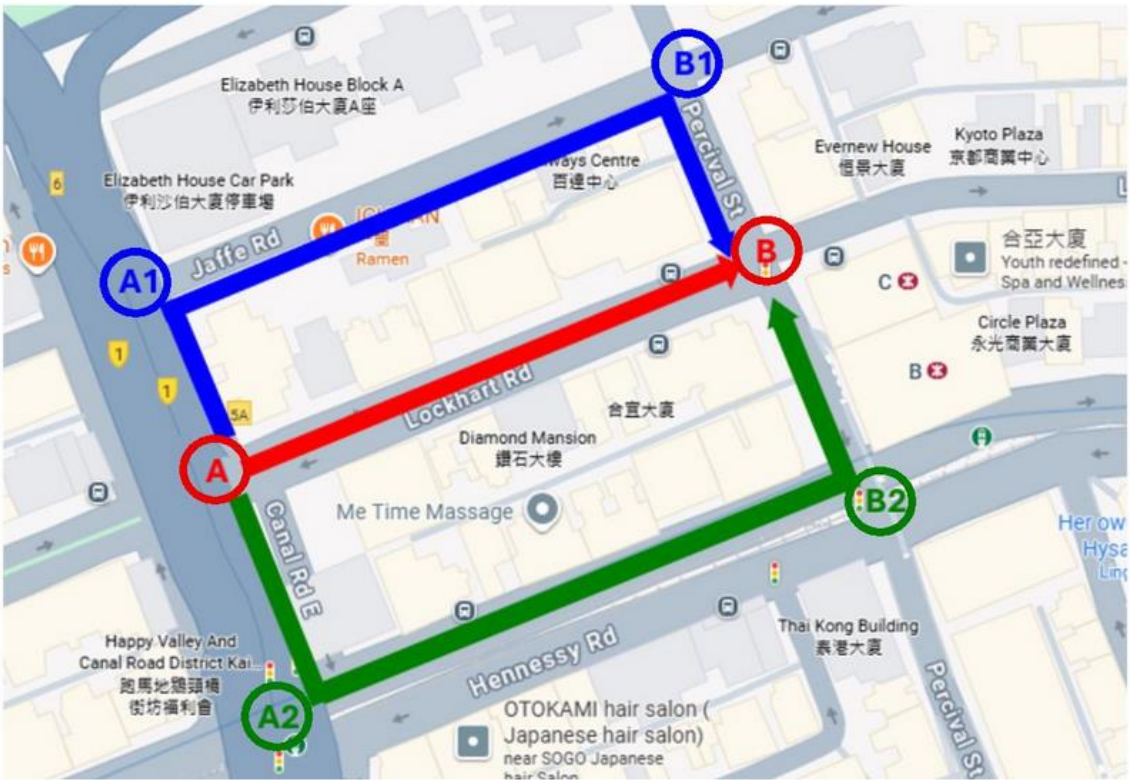

Figure 1. Possible bypasses for the planned block [A, B] are [A, A1, B1, B] and [A, A2, B2, B]

Suppose the transit time of each vehicle passing through a block is recorded and stored in MongoDB database. As more vehicles pass through the block, large amounts of their transit time formulate a big training data set. With these data, the mean transit time $\bar{x}$ and the standard deviation of the transit time σ can be obtained. Also, based on these data, the fastest path from a source to a destination can be planned by using Djikstra's algorithm [1]. For example, Figure 2 shows the fastest path with the source (denoted by s) at a junction denoted by node[0] and the destination (denoted by d) at node[4]. This fastest path from node[0] to node[4] passes through node[1], node[2], and node[3].

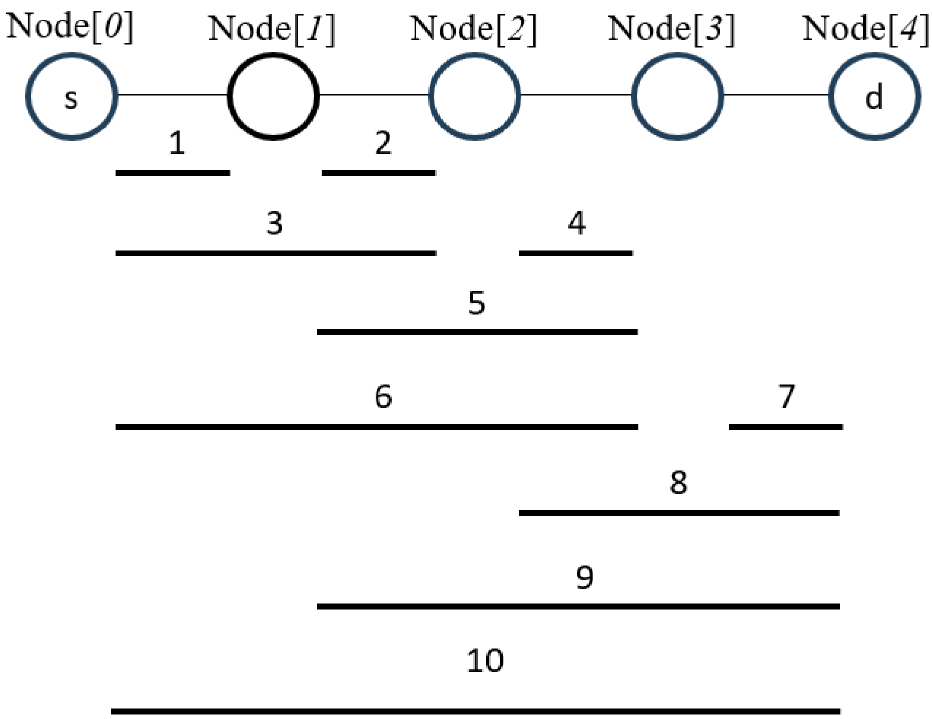

Figure 2. Bypass Optimization Algorithm

This big training data set can be analyzed by binary classification in machine learning to classify the input data into one of two mutually exclusive classes - one class is "no congestion" in which the amounts of transit time are clustered around $\bar{x}$ while the other class is "congestion" in which the amounts of transit time exceed $\bar{x}$ + 3σ, as roughly 99.7% of the data is within 3 standard deviations of the average under normal distribution and the vehicle with the transit time falls outside 3 standard deviations of the average is regarded as "congested". With the aid of binomial logistic regression classification algorithm, the number of cases in either "no congestion" class or "congestion" class can be obtained and therefore, the probability of traffic congestion ρ at the block can be computed.

Suppose a block between node[0] and node[1] is denoted by [0, 1]. For each block (i.e., [0, 1], [1, 2], [0, 2], [2, 3], [1, 3], [0, 3], …), an optimal bypass with the total transit time < $\bar{x}$ + 3σ is searched. Figure 1 shows two possible bypasses for the block with the junction A and the junction B. To locate the optimal bypass for [a, b], the following assumptions and notations are used:

1. [a, b] contains the two-junction blocks l_1, l_2, … l_w with the probabilities of traffic congestion ρ_1, ρ_2, … ρ_w.
2. Suppose there are two possible bypasses for [a, b] – one with two-junction blocks l_{w+1}, l_{w+2}, … l_{w+m} with the probabilities of traffic congestion ρ_{w+1}, ρ_{w+2}, … ρ_{w+m} while the other with

two-junction blocks l_{w+m+1}, l_{w+m+2}, … l_{w+m+n} with the probabilities of traffic congestion ρ_{w+m+1}, ρ_{w+m+2}, … ρ_{w+m+n}.

3. Suppose $A = 1 - \rho$. A is termed availability.
4. Based on conditional probabilities, A for l_{w+1}, l_{w+2}, … l_{w+m} is computed as follows:

$$\prod_{i=1}^{w}(1-\rho_i)+\left[1-\prod_{i=1}^{w}(1-\rho_i)\right]\prod_{j=w+1}^{w+m}(1-p_j)$$

and A for l_{w+m+1}, l_{w+m+2}, … l_{w+m+n} is computed as follows:

$$\prod_{i=1}^{w}(1-\rho_i)+\left[1-\prod_{i=1}^{w}(1-\rho_i)\right]\prod_{j=w+m+1}^{w+m+n}(1-p_j)$$

5. The optimal bypass is the bypass for a block with the highest availability. If A for l_{w+1}, l_{w+2}, … $l_{w+m} > A$ for l_{w+m+1}, l_{w+m+2}, … l_{w+m+n}, set l_{w+1}, l_{w+2}, … l_{w+m} as the optimal bypass for [a, b]. Otherwise, set l_{w+m+1}, l_{w+m+2}, … l_{w+m+n} as the optimal bypass for [a, b].

A bypass structure can be an optimal bypass or concatenation of some optimal bypasses for a block starting from the source. The number above a line in Figure 2 indicates the sequence of optimal bypass structure or optimal bypass searches. Step 1 finds the optimal bypass structure for [0, 1], step 2 finds the optimal bypass for [1, 2], step 3 finds the optimal bypass structure for [0, 2], and so on. The search continues until reaching the destination at node[4].

Suppose $S(0, x)$ is the availability of the bypass structure for [0, x]. Suppose $P(j, x)$ is the highest availability between node[j] and node[x]. Then, the optimal bypass structure (i.e., the optimal bypass or concatenation of the optimal bypasses) is formed by computing:

$$S(0,x)\begin{cases} 1 & when\ x=0 \\ P(0,1) & when\ x=1 \\ \max\limits_{j=0,1,\ldots x-1}\{S(0,j)\times P(j,x)\} & when\ x>1 \end{cases}$$

To search for the optimal bypass structure for the fastest path from node[*0*] to node[*4*] in Figure 2, the bypass optimization algorithm performs the following steps:

Step 1: $x = 1$, the optimal bypass structure with $S(0,1) = P(0,1)$ is found.
Step 2: the optimal bypass with $P(1,2)$ is found.
Step 3: $x = 2$, the optimal bypass structure with

$$S(0,2) = \max\{P(0,2), S(0,1)\times P(1,2)\}$$

is found. This optimal bypass structure contains either one optimal bypass with $P(0,2)$ or concatenation of two optimal bypasses with $P(0,1)$ and $P(1,2)$.

Step 4: the optimal bypass with $P(2,3)$ is found.
Step 5: the optimal bypass with $P(1,3)$ is found.
Step 6: $x = 3$, the optimal bypass structure with

$$S(0,3) = \max\{P(0,3), S(0,2)\times P(2,3), S(0,1)\times P(1,3)\}$$

is found. This optimal bypass structure contains either one optimal bypass with $P(0,3)$, concatenation of the optimal bypasses with $S(0,2)$ and $P(2,3)$ or concatenation of the optimal bypasses with $S(0,1)$ and $P(1,3)$.

Step 7: the optimal bypass with $P(3,4)$ is found.
Step 8: the optimal bypass with $P(2,4)$ is found.
Step 9: the optimal bypass with $P(1,4)$ is found.
Step 10: $x = 4$, the optimal bypass structure with

$$S(0,4) = \max \{P(0,4), S(0,3)\times P(3,4), S(0,2)\times P(2,4), S(0,1)\times P(1,4)\}$$

is found. This optimal bypass structure contains either one optimal bypass with $P(0,4)$, concatenation of the optimal bypasses with $S(0,3)$ and $P(3,4)$, concatenation of the optimal bypasses with $S(0,2)$ and $P(2,4)$, or concatenation of the optimal bypasses with $S(0,1)$ and $P(1,4)$.

5. Reliability and Accuracy of the Algorithm

The reliability and accuracy of the bypass optimization algorithm can be proved by induction. In Figure 2, the planned fastest path consists of the blocks (i.e., [0, 1], [0, 2], [0, 3], and [0, 4]). On this planned path, the base case is $x = 1$.

When $x = 1$, $[0, x]$ contains 1 two-junction block [0, 1] with one junction at node[0] and the other junction at node[1]. The optimal bypass with $S(0,1) = P(0,1)$ is found. Then, the induction steps work as follows:

When $x = 2$, the block [0, 2] can contain the bypass structure with:

- the optimal bypass structure for [0, 1] and optimal bypass for the two-junction block [1, 2]. Each end of these blocks [0, 1] and [1, 2] is a junction. The two junctions for [0, 1] are node[0] and node[1] while the two junctions for [1, 2] are node[1] and node[2], or
- the optimal bypass for the three-junction block [0, 2].

The highest availability of the bypass structure for [0, 2] can be computed by obtaining the maximum availability among the bypass structures with:

- $S(0,1)\times P(1,2)$
- $P(0,2)$

So, $S(0,2)$ is the maximum of these. Then, the optimal bypass structure for [0, 2] with $S(0, 2)$ can be constructed.

When $x = 3$, the block [0, 3] can contain the bypass structure with:

- the optimal bypass structure for [0, 2] and the optimal bypass for the two-junction block [2, 3],
- the optimal bypass structure for [0, 1] and the optimal bypass for the three-junction block [1, 3] with the three junctions at node[1], node[2], and node[3], or
- the optimal bypass for the four-junction block [0, 3].

The optimal bypass structure for [0, 3] with $S(0, 3)$ which is the maximum availability among:

- $S(0,2)\times P(2,3)$
- $S(0,1)\times P(1,3)$
- $P(0,3)$

When $x = 4$, the block [0, 4] can contain the bypass structure with:

- the optimal bypass structure for [0, 3] and the optimal bypass for the two-junction block [3, 4],
- the optimal bypass structure for [0, 2] and the optimal bypass for the three-junction block [2, 4],
- the optimal bypass structure for [0, 1] and the optimal bypass for the four-junction block [1, 4], or
- the optimal bypass for [0, 4]

The optimal bypass structure for [0, 4] with $S(0, 4)$ which is the maximum availability among:

- $S(0,3)\times P(3,4)$
- $S(0,2)\times P(2,4)$
- $S(0,1)\times P(1,4)$
- $P(0,4)$

So, the bypass optimization algorithm can guarantee the optimal bypass structure with the maximum availability $S(0,x)$ where node[0] is the source and node[x] is the destination.

6. CONCLUDING REMARKS AND FUTURE WORK

This proposed study aims to design the machine learning model for bypass optimization algorithm to set up the optimal bypass structure when planning the shortest path from a source to a destination for a road transport for emergency services in Hong Kong. This algorithm can be evaluated in terms of its performance and stakeholders' acceptance of this technology. To evaluate the performance of this algorithm, numerical analysis can be used with time complexity and simulation of detour cases. For this simulation, the processing time required for the detour cases with the use of the bypass optimization algorithm is used to compare with the processing time for the detour cases without the use of the algorithm and then examine whether the proposed algorithm can lead to more efficient transportation.

To maintain sustainability of technology, it is important to know whether the technology can help the technology users and whether these users accept using that technology [9–10]. The sustainability of the bypass optimization algorithm can be evaluated in future research studies by exploring the stakeholders' acceptance of this algorithm.

Thereafter, the analytical and simulation results of this proposed machine learning model for bypass optimization algorithm together with the stakeholders' acceptance of the algorithm provide support for the actual development of the algorithm. This development also inspires the design and development of traffic sensors (i.e., IoTs) at a block of a road in some traffic-busy areas in Hong Kong to capture every vehicle's transit time. These streaming data from the traffic sensors can be used to determine traffic congestion conditions which provide tremendous data sets for computing accurate probabilistic models for constructing the optimal bypasses for any road transport for emergency services.

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AUTHOR

Simon Wong received the BCompSci degree from the University of Minnesota, USA, in 1993, the MPhil degree from the Hong Kong Polytechnic University (PolyU) in 1997 and the EdD degree from the University of Leicester, UK, in 2012. After obtaining the MPhil degree, Simon continued his teaching work at PolyU. Then, he became a Senior Consultant for Oracle, specializing in consultancy and training of Oracle systems for a large variety of sectors. Since joining School of Professional Education and Executive Development, PolyU, he has been teaching various information technology courses. His research interests include information technology education research, students' and teachers' perceptions of student response systems, learning effectiveness of multimedia learning, blockchain technology and machine learning.