A STUDY ON THE PREDICTION OF TRAFFIC BOTTLENECKS AND ROUTE GUIDANCE STRATEGIES FOR FREEWAY CORRIDORS

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Abstract: Traffic bottlenecks on highways are generally caused by either insufficient capacities to accommodate traffic demands or non-recurrent traffic congestion such as traffic incidents. From a network-wide perspective, traffic bottlenecks occur most likely as a result of the unbalanced traffic flow distributions on freeway corridors. To analyze the potential network flow distribution issues, traffic assignment models with link capacity side constraints are desirable to solve highway network bottleneck problems. More importantly, one can design beneficial route guidance strategies according to the results of traffic assignment.
In the present research, an operational traffic assignment model with link capacity side constraints has been developed to on-line predict traffic bottlenecks on freeway corridors. A set of route guidance control strategies for freeway motorists are proposed in accordance with traffic assignment results. A local freeway/highway corridor was employed to test the feasibility of the proposed model. The test results indicate that the proposed model is capable of predicting traffic bottlenecks, and corresponding route guidance strategies provide suitable route diversion and trip rerouting suggestions.

Key Words: Traffic Bottleneck, Route Guidance, Traffic Assignment

1. INTRODUCTION

Traffic bottlenecks on highways are generally caused by the following factors. Firstly, there may be insufficient roadway capacity to accommodate high traffic demands. In such a case, recurrent traffic congestion at specific roadway sections is usually observed. Secondly, traffic bottlenecks may be induced due to non-recurrent traffic congestion, such as traffic incidents that cause temporary reduction of highway capacity. Both cases stated above may cause significant traffic congestion and extra travel times if corresponding traffic control strategies and/or actions are not appropriately taken. State-of-the-art research concerning the predictions of traffic bottlenecks is mainly based on traffic engineering and/or traffic flow theory. Lighthill and Whitham (1955) firstly proposed kinematics wave theory to describe macroscopic traffic flow behaviors. Traffic flows around bottlenecks were specifically modeled using shockwave theory. Messer *et al*. (1973) provided highway travel time prediction models under the condition of highway partial closure. They investigated the problem using an integrated concept of shockwave theory and Greenshields' model. Desirable traffic re-routing information is provided to motorists as a result of travel time predictions of alternative routes. More recent research incorporated queuing theory into the analysis of traffic bottlenecks. Yang and Yagar (1994) proposed a bi-level programming formulation of traffic assignment and traffic control problem in a freeway-arterial corridor system. The upper-level problem is to determine ramp metering rates that optimize system performance criterion, taking into account driver's route choice behavior. In solving the problem, they presented a sensitivity analysis approach for the queuing network equilibrium problem. Chin (1996) analyzed traffic delays at the upstream of traffic bottlenecks. Queuing theory analysis was employed to predict queuing probabilities and accumulated queuing vehicles. On the other hand, the problem could also be formulated as a short-term flow fluctuation by applying shockwave theory. Spatial distributions of traffic flows and speeds are explicitly captured by a shockwave theory based model. Cho *et al*. (2001) further investigated the problem using shockwave theory under the assumption of flow conservation. In solving the problem, method of characteristics is applied to provide vehicle trajectories and traffic densities. Numerical simulation experiments using finite difference method at traffic bottlenecks of a two-lane highway were conducted, and preliminary results demonstrated the validity of the proposed models. The above research has shown their capabilities in capturing flow propagation characteristics on a specific link or roadway section. However, from a network-wide perspective, traffic bottlenecks occur most likely as a result of unbalanced distribution of traffic flows on freeway corridors. Moreover, traffic diversion during traffic incidents becomes an important issue in modern traffic control and management area. Traffic engineering and/or traffic flow theory based methods are not capable of providing network-wide traffic diversion and/or trip re-routing policies. Therefore, relevant methods in the literature are not suitable for this purpose.

To analyze the potential network flow distribution issues, traffic assignment models with link capacity side constraints are desirable to solve highway network bottleneck problems. More importantly, one can design beneficial route guidance strategies according to traffic assignment results. Therefore, traffic assignment based models are crucial for the predictions of traffic bottlenecks on a freeway network. In the present research, an operational traffic assignment model with link capacity side constraints has been developed to on-line predict traffic bottlenecks on freeway corridors. A set of route guidance control strategies for freeway motorists are proposed in accordance with traffic assignment results. To demonstrate the feasibility of applying the present methodology to freeway control and management purposes, a local freeway/highway network composing of freeways, expressways, local arterials, and connectors was tested. The test results indicate that the proposed model is capable of predicting traffic bottlenecks, and corresponding route guidance strategies provide suitable route diversion and trip rerouting suggestions. More significantly, better network performance is possibly achieved as a result of traffic re-distribution. The path-based traffic assignment model with link capacity side constraints has shown its great potentials for freeway on-line operational and management purposes.

2. PROBLEM FORMULATION AND MODEL SPECIFICATION

In view of the characteristics of the problem identified above, the present research proposes a traffic assignment model based on user equilibrium assumption and link capacity side constraints. The model considers both motorists' route choice behaviors and highway physical constraints. The following subsections describe the details of the proposed model.

2.1 Link Capacity Constraints

Under Wardrop's first principle of equilibrium, in making desirable route choice decisions, it is assumed that highway users in the observed network possess full information about the prevailing network. However, since the issue of link capacity constraints is incorporated into the proposed model, therefore the user equilibrium principle is modified accordingly. Specifically, when the user equilibrium condition under link capacity constraints is achieved, the link costs associated with the paths being assigned traffic flows for a given OD pair can be specified as follows (Larsson and Patriksson, 1995):

$$c_{p_1}^{rs} \le c_{p_2}^{rs} \le c_{p_3}^{rs} \le .... \le c_{p_m}^{rs} = c_{p_{m+1}}^{rs} = ... = c_{p_l}^{rs} \qquad (1)$$

In equation (1), even though the travel costs of the paths being used, $c_{p_1}^{rs}...c_{p_{m-1}}^{rs}$ are less than those of the paths are not used, due to link capacity constraints, the traffic flows at the paths have reached their capacities, resulting in the queuing delays. Thus, to realistically capture user's route choice behaviors under link capacity constraints, the cost function of alternative paths for a given OD pair should account for both link travel times and queuing delays. Therefore, one can reformulate (1) as follows:

$$\breve{c}_{p_1}^{rs} = \breve{c}_{p_2}^{rs} = \breve{c}_{p_3}^{rs} = ... = \breve{c}_{p_m}^{rs} = \breve{c}_{p_{m+1}}^{rs} = ... = \breve{c}_{p_l}^{rs} \qquad (2)$$

where, $\breve{c}_p^{rs} = c_p^{rs} + \beta_p^{rs}$

In equation (2), $\breve{c}_p^{rs}$ is defined as the "generalized travel time" of the p^{th} path given OD pair *rs*. Note that the p^{th} path can be composed of several links traversing on the path. Each link's generalized travel time is including link travel times and queuing delays. The relationship between link travel time with respected to link performance function and capacity constrained queuing delay can be depicted in figure 1.

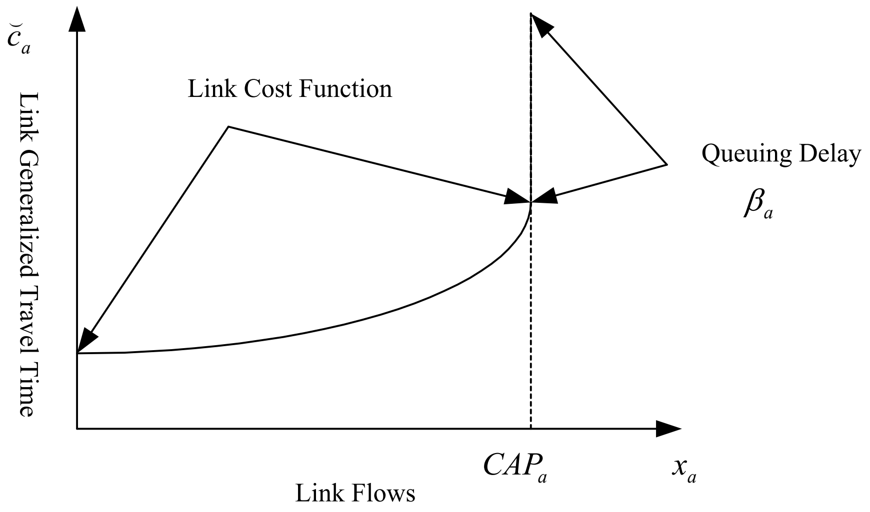

Figure 1. Relationship between Link Flow and Generalized Travel Time

In sum up, the user equilibrium principle under link capacity constraints is redefined as follows:

> *Given a specific OD pair, the generalized travel times of the paths being used are less than or equal to those of the paths are not used. The generalized travel times are composed of path travel times and queuing delays associated with the paths being used.*

The above principle can also be specified mathematically as follows:

$$\breve{c}_p^{rs*}\begin{cases} = \breve{\pi}^{rs} & \text{if } h_p^{rs*} > 0 \\ \geq \breve{\pi}^{rs} & \text{if } h_p^{rs*} = 0 \end{cases} \quad \forall r, s, p \tag{3}$$

2.2 UE Model under Link Capacity Constraints

The modified UE model can be further formulated as follows:

$$\min z(\mathbf{x}) = \sum_a \int_0^{x_a} c_a(\omega) d\omega \tag{4}$$

subject to

(a) Flow conservation equation:

$$\sum_p h_p^{rs} = \overline{q}^{rs} \quad \forall r, s \tag{5}$$

(b) Non-negativity equation:

$$h_p^{rs} \geq 0 \quad \forall r, s, p \tag{6}$$

$$\varphi_a \geq 0 \quad \forall a \tag{7}$$

(c) Link-path incidence equation:

$$x_a = \sum_{rs} \sum_p h_p^{rs} \delta_{ap}^{rs} \quad \forall a \tag{8}$$

$$\overline{\delta}_{ap}^{rs} = \{0,1\} \quad \forall r, s, a, p \tag{9}$$

(d) Link capacity constraint equation:

$$g_a = x_a - CAP_a + \varphi_a = 0 \quad \forall a \tag{10}$$

In solving the above optimization problem, one can incorporate Lagrangean multipliers $\{\breve{\pi}^{rs}\}$ and $\{\beta_a\}$ into the objective function, and obtain the following Lagrangean function:

$$L(z,\pi,\beta) = \sum_a \int_0^{x_a} c_a(\omega)d\omega + \sum_{rs} \breve{\pi}^{rs}\left(\sum_p h_p^{rs} - \bar{q}^{rs}\right) + \sum_a \beta_a g_a \tag{11}$$

Take the partial derivative of (11) with respect to path flow $\{h_p\}$, Lagrangean multipliers $\{\breve{\pi}^{rs}\}$ and $\{\beta_a\}$, one can obtain the first order condition of the formulation as follows:

$$h_p^{rs}\left[\breve{c}_p^{rs} - \breve{\pi}^{rs}\right] = 0 \quad \forall r,s,p \tag{12}$$

$$\breve{c}_p^{rs} = \sum_a (c_a + \beta_a)\delta_{ap}^{rs} \quad \forall r,s,p \tag{13}$$

$$\breve{c}_p^{rs} - \breve{\pi}^{rs} \geq 0 \quad \forall r,s,p \tag{14}$$

$$\sum_p h_p^{rs} = \bar{q}^{rs} \quad \forall r,s \tag{15}$$

$$h_p^{rs} \geq 0 \quad \forall r,s,p \tag{16}$$

$$\beta_a\left[x_a - CAP_a\right] = 0 \quad \forall a \tag{17}$$

$$x_a - CAP_a \leq 0 \quad \forall a \tag{18}$$

$$\beta_a \geq 0 \quad \forall a \tag{19}$$

Equations (12)~(16) represent the compensated relaxation relationships in route choice behaviors, which means the generalized travel times of the paths being assigned traffic flows for a given OD pair are equal to the minimum generalized path travel times, otherwise the flows on the specific paths would be forced to be zero. In addition, equations (17)~(19) depict the compensated relaxation relationships between link cost and link capacity. That is, when the flow on a specific link is less than its capacity, then the queuing delay is zero; otherwise, the queuing delay β_a is greater than zero.

By employing appropriate computing algorithms, one can solve the problem and obtain link travel times, queuing delays, and other crucial traffic variables for on-line traffic control and management purposes.

3. COMPUTATING ALGORITHM

In solving the above UE model with link capacity constraints, one can employ Augmented Lagrangean Dual (ALD) Algorithm (Larsson and Patriksson, 1995) and Disaggregate Simplicial Decomposition (DSD) Method (Larsson and Patriksson, 1992). However, the ALD method requires the assumption of artificial variables. As far as computational complexity is concerned, ALD based methods are complicated to implement. In view of the computational difficulty of the ALD method, the present research proposes a simplified

Lagrangean method, namely Lagrangean-Gradient Projection method (the L-GP method) to solve the problem. Specifically, by applying the Lagrangean method to the UE with link capacity constraints problem, the design is to solve the primal and dual variables iteratively:

1. *Solving the primal variables of the Lagrangean form of objective function:*

$$\min_{\mathbf{x}} L\left(z(\mathbf{x}),\bar{\beta}\right) = z(\mathbf{x}) + \sum_a \bar{\beta}_a\left[x_a - CAP_a\right] \quad \forall \mathbf{x} \in \Omega \tag{20}$$

where Ω is the feasible solution areas under the conditions of equations (5)~(10).

2. *Solving the dual variables of the Lagrangean form of objective function:*

$$\max_{\beta} L\left(z(x),\beta\right) = z(\bar{\mathbf{x}}) + \sum_a \beta_a\left[x_a - CAP_a\right] \tag{21}$$

subject to

$$\beta_a \geq 0 \quad \forall a \tag{22}$$

In the above problem formulation, the solution to the primal problem (20) is the equilibrium solution of user path choice model, and is obtained by path-based Gradient Projection method. On the other hand, the dual problem (21~22) is iteratively solved by updating the dual variables using equation (23) until convergence is achieved. Since the proposed computing algorithm is composed of Lagrangean method and GP method, therefore it is named the "L-GP method".

$$\beta_a^{l+1}\begin{cases} = \beta_a^l + \lambda\left(c_a^l(\mathbf{x}) - c_a^l(CAP_a)\right), if\ x_a^l \geq CAP_a \\ = 0 \qquad\qquad\qquad\qquad\qquad\ , if\ x_a^l < CAP_a \end{cases} \quad \forall a, 0 < \lambda \leq 1 \tag{23}$$

Furthermore, the steps in obtaining the solutions of the UE problem with link capacity constraints are outlined below:

<u>Step 1</u>: Let l=0, and set the initial value of Lagrangean multipliers equal to zero.

<u>Step 2</u>: Solve the primal problem using GP method, if the solutions $\left\{x_a^{l+1}\right\}$ do not meet the link capacity constraints, for example: $\max_a\left\{x_a^{l+1} - CAP_a\right\} > \varepsilon = 0.01$, then continue the following step; otherwise, the final solutions are obtained and corresponding generalized travel times $\breve{c}_a$ are calculated in light of the estimated link flows.

<u>Step 3</u>: Update Lagrangean multipliers $\left\{\beta_a^{l+1}\right\}$ using equation (23), and return to step 2.

The above problem formulations and corresponding computation algorithms provide better insight to highway traffic bottleneck problem. More importantly, the proposed mechanism is capable of generating the information of used paths and corresponding path flows, path travel times, queuing delays, and potential traffic bottlenecks. The valuable information is beneficial to predict traffic bottlenecks for freeway corridors, and desirable traffic control strategies and routing policies can be prepared and provided to highway motorists in making better travel decisions.

4. NUMERICAL EXAMPLE AND DEMONSTRATION

4.1 Experimental Design

To demonstrated the capability of the proposed framework, a local freeway corridor consisting of national freeway systems, provincial intercity expressways, and local arterials and connectors as shown in figure 2. The distance between nodes in the test network was calculated by referring the digital map released by the government office in 2000. In addition, free-flow travel times for various levels of highway systems were estimated by obtaining their corresponding speed limits and the distance between nodes. Since the issue of highway capacity constraint is one of the focusing points of the research, we imposed different capacity quantities for various levels of highways. Moreover, link cost function for each roadway section was assumed to comply with the form of FHWA's, as shown in equation (24). On the other hand, the demand side data in terms of OD demands for specific OD pairs were assumed for numerical analysis and demonstration purposes as shown in table 1. In summary, data concerning both the supply and demand sides in the experiments were prepared in accordance with local highway network and traffic characteristics.

$$c(x_a) = c_{a_0}\left(1 + 0.15\left(\frac{x_a}{CAP_a}\right)^4\right) \tag{24}$$

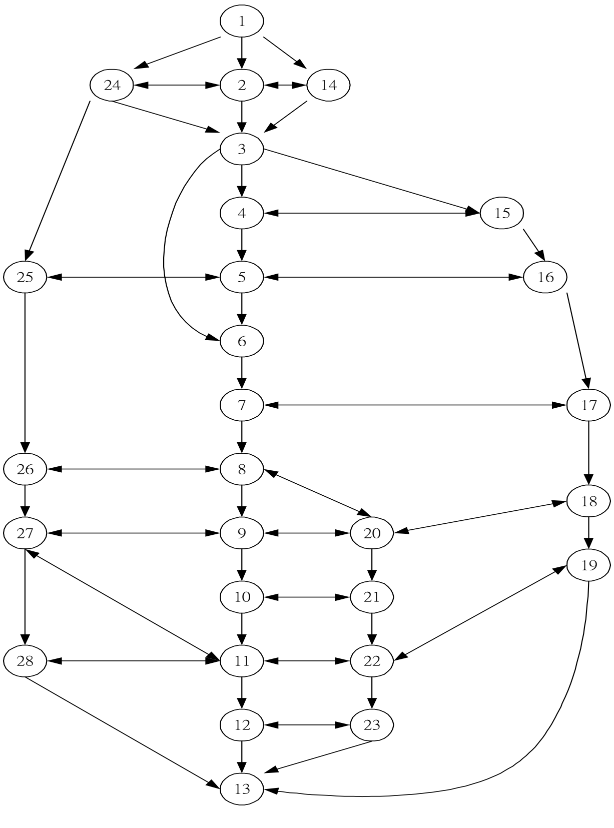

Figure 2. Test Network Configuration

Table 1. OD Demands for Each OD Pair

OD Pair	1→5	1→8	1→13	3→8	4→8	4→18
Demands (p.c.u.)	840	540	1050	520	520	430
OD Pair	4→27	5→13	8→13	15→13	15→27	
Demands (p.c.u.)	550	560	1600	1060	1030	

4.2 Solutions Searching and Programming

According to the test network configuration and OD demands specified previously, we have developed the relevant programming based on the L-GP method using Borland C^{++} version 5.02. The results obtained below were implemented at the personal computer with CPU of Pentium III-800.

4.3 Results and Analysis

Based on the experimental design stated above, we solve the illustrated example using the L-GP method. Table 2 shows the numerical results in terms of path flows, path travel times, queuing delays, and generalized travel times for each OD pair. It can be found from table 2 that the equilibrium conditions specified in (3) are basically satisfied, even though there exists different magnitudes of travel times and queuing delays of the paths being used for each OD pair. Moreover, the traffic assignment results indicate that the generalized travel times under link capacity constraints are equal to those without capacity constraints. Therefore, the proposed model is able to capture the physical characteristics of roadway and provide valid path flows and corresponding travel cost indices.

Table 3 further demonstrates the detailed information for each link after implementing the proposed L-GP algorithm. Several outcomes are found and outlined below:

1. The flow conservation and non-negativity constraints are satisfied.
2. For those assigned traffic flows reached their capacities, queuing delays are found, while queuing delays are zero for those link flows that have not yet reached their capacities.
3. For those links with non-zero queuing delays in the observed network (e.g., those numbers in shaded cells), they are the potential roadway sections causing traffic bottlenecks.

Table 2. Path Flows for Each OD Pair

OD Pair	Assigned Path	Traffic Volume	Travel Time	Queuing Delay	Generalized Travel Time
1→5	1→2→3→4→5	800.36	16.31	16.05	32.36
	1→24→3→4→5	39.64	19.74	12.62	
1→8	1→2→3→6→7→8	500.39	32.56	59.00	91.56
	1→24→3→6→7→8	39.61	36.00	55.56	
1→13	1→2→3→6→7→8→9→10→11→12→13	3.06	66.47	64.35	130.82
	1→24→25→26→27→28→13	260	130.82	0.00	
	1→24→3→6→7→8→9→20→18→19→13	81.57	74.80	56.02	
	1→24→3→6→7→8→20→18→19→13	0.02	75.26	55.56	
	1→24→3→15→16→17→18→19→13	9.18	71.26	59.56	
	1→2→3→6→7→8→20→18→19→13	11.63	71.82	59.00	
	1→2→3→15→16→17→18→19→13	10.83	67.83	62.99	
	1→2→3→6→7→8→9→20→18→19→13	673.73	71.36	59.46	
3→8	3→6→7→8	520.00	24.63	55.56	80.19
4→8	4→5→6→7→8	520.00	17.24	68.18	85.42
4→18	4→5→6→7→8→9→20→18	81.73	27.35	68.64	95.99
	4→5→6→7→8→20→18	8.27	27.81	68.18	
	4→15→17→18	340.00	36.43	59.56	
4→27	4→5→25→26→27	550.00	45.26	45.71	90.97
5→13	5→6→7→8→9→10→11→12→13	476.01	49.76	60.91	110.67
	5→6→7→8→9→20→18→19→13	83.94	54.65	56.02	
	5→6→7→8→20→18→19→13	0.05	55.11	55.56	
8→13	8→9→20→18→19→13	79.04	38.79	0.47	39.26
	8→9→10→11→12→13	1520.93	33.90	5.36	
	8→20→18→19→13	0.03	39.26	0.00	
15→13	15→16→17→18→19→13	1060.00	53.29	59.56	112.85
15→27	15→16→5→25→26→27	450.00	66.93	33.09	100.02
	15→16→17→18→20→9→27	580.00	40.46	59.56	

Table 3. Details of Link Flows

Link	Free-flow Travel Time	Queuing Delay	Travel Time	Generalized Travel Time	Link Volume	Link Capacity
1-2	1.50	0.75	1.72	2.47	2000.00	2000.00
1-14	6.00	0.00	6.00	6.00	0.00	1000.00
1-24	4.08	0.00	4.10	4.10	430.00	1000.00
2-3	5.40	2.69	6.21	8.90	2000.00	2000.00
2-14	0.12	0.00	0.12	0.12	0.00	1000.00
2-24	11.28	0.00	11.28	11.28	0.00	1000.00
3-4	6.96	0.00	6.99	6.99	840.00	2000.00
3-6	12.30	0.00	13.59	13.59	1830.00	2000.00
3-15	6.60	0.00	6.60	6.60	20.00	2000.00
4-5	1.20	12.62	1.38	14.00	2000.00	2000.00
4-15	11.80	0.00	11.82	11.82	340.00	1000.00

5-6	4.80	0.00	4.82	4.82	1170.00	3000.00
5-16	12.40	0.00	12.40	12.40	0.00	1000.00
5-25	11.40	33.09	13.11	46.20	1000.00	1000.00
6-7	4.68	50.79	5.38	56.17	3000.00	3000.00
7-8	4.92	4.77	5.66	10.43	3000.00	3000.00
7-17	18.90	0.00	18.90	18.90	0.00	1000.00
8-9	1.86	0.46	2.14	2.60	3000.00	3000.00
8-20	5.28	0.00	5.28	5.28	20.00	1000.00
8-26	18.50	0.00	18.50	18.50	0.00	1000.00
9-10	2.88	0.00	2.97	2.97	2000.00	3000.00
9-20	2.60	0.00	2.68	2.68	1000.00	1500.00
9-27	8.07	0.00	8.10	8.10	580.00	1500.00
10-11	3.24	0.00	3.34	3.34	2000.00	3000.00
10-21	3.24	0.00	3.24	3.24	0.00	1000.00
11-12	4.02	0.00	4.14	4.14	2000.00	3000.00
11-22	0.96	0.00	0.96	0.96	0.00	1000.00
11-27	35.10	0.00	35.10	35.10	0.00	500.00
11-28	16.71	0.00	16.71	16.71	0.00	1000.00
12-13	18.54	4.89	21.32	26.21	2000.00	2000.00
12-23	0.12	0.00	0.12	0.12	0.00	1000.00
14-2	0.12	0.00	0.12	0.12	0.00	1000.00
14-3	11.80	0.00	11.80	11.80	0.00	2000.00
15-4	11.80	0.00	11.80	11.80	0.00	1000.00
15-16	4.07	0.00	4.34	4.34	2450.00	3000.00
16-5	18.60	0.00	18.71	18.71	450.00	1000.00
16-17	15.80	59.56	18.17	77.73	2000.00	2000.00
17-7	18.90	0.00	18.90	18.90	0.00	1000.00
17-18	2.04	0.00	2.10	2.10	2000.00	3000.00
18-19	5.04	0.00	5.19	5.19	2010.00	3000.00
18-20	5.13	0.00	5.15	5.15	580.00	1500.00
19-13	22.80	0.00	23.49	23.49	2010.00	3000.00
19-22	7.11	0.00	7.11	7.11	0.00	1000.00
20-8	5.28	0.00	5.28	5.28	0.00	1000.00
20-9	2.60	0.00	2.61	2.61	580.00	1500.00
20-18	5.13	0.00	5.29	5.29	1020.00	1500.00
20-21	6.00	0.00	6.00	6.00	0.00	1000.00
21-10	3.24	0.00	3.24	3.24	0.00	1000.00

21-22	4.68	0.00	4.68	4.68	0.00	1000.00
22-11	0.96	0.00	0.96	0.96	0.00	1000.00
22-19	7.11	0.00	7.11	7.11	0.00	1000.00
22-23	9.24	0.00	9.24	9.24	0.00	1000.00
23-12	0.12	0.00	0.12	0.12	0.00	1000.00
23-13	34.50	0.00	34.50	34.50	0.00	1000.00
24-2	11.28	0.00	11.28	11.28	0.00	1000.00
24-3	7.27	0.00	7.27	7.27	170.00	2000.00
24-25	51.51	0.00	51.55	51.55	260.00	1000.00
25-5	11.40	0.00	11.40	11.40	0.00	1000.00
25-26	22.54	0.00	24.22	24.22	1260.00	1500.00
26-8	18.50	0.00	18.50	18.50	0.00	1000.00
26-27	6.09	0.00	6.54	6.54	1260.00	1500.00
27-9	8.07	0.00	8.07	8.07	0.00	2000.00
27-11	28.08	0.00	28.08	28.08	0.00	500.00
27-28	17.40	0.00	17.40	17.40	260.00	1500.00
28-11	16.71	0.00	16.71	16.71	0.00	1000.00
28-13	27.00	0.00	27.00	27.00	260.00	1500.00

5. ROUTE GUIDANCE STRATEGIES FOR TRAFFIC BOTTLENECKS

By employing the theoretical framework of the L-GP model, a traffic control center is able to foresee the near future traffic conditions and pre-specify desirable traffic control and/or route guidance strategies in alleviating potential traffic congestion caused by traffic bottlenecks. A set of general guidelines in preparing desirable route guidance and policies for practical applications are presented as follows.

5.1 General Guidelines for Route Guidance

The basic guidelines in providing desirable route guidance strategies are outlined below:

1. Activate route guidance strategies at a few interchanges upstream of the traffic bottleneck.
2. The selection of appropriate traffic diversion points should account for the prevailing traffic conditions both at alternative routes and connectors.
3. The alternative routes with higher functionality possess higher priority to divert traffic in the congested area.
4. If the suggested alternative routes cannot reach user's specific destination, then the other alternatives with lower highway functionality are suggested.

5.2 Policies for Practical Applications

Following the results analyzed in section 4.3 and table 3, we may obtain the potential bottleneck roadway sections by looking at the column of queuing delay with non-zero elements. To provide suitable control policies in alleviating traffic congestion, besides the current traffic conditions in the network are considered, one should take highway users' perspectives into considerations. Specifically, we conducted a local survey of motorists on the investigation of the maximum delay that a motorist can resist. The results indicated that, in general, motorists could resist the maximum queuing delay less than 30 minutes. Based on the findings, we propose the following control policies of route guidance for practical application purposes.

Policy 1: If the duration of congestion is estimated by 30 minutes or less, then no route guidance related actions are taken.

Policy 2: If the duration of congestion is estimated greater than 30 minutes but less than 1 hour, then the following actions are taken:

(1) If the traffic flows among alternative routes are significantly different, then divert the traffic to the one with higher surplus capacity.
(2) If the surplus capacities among alternative routes are about the same level, then provide the motorists with the specific alternative route of the shortest connecting distance.

Policy 3: If the duration of congestion is estimated greater than 1 hour, then the following actions are taken:

(1) Divert traffic at the interchanges upstream and far from the bottleneck.
(2) Divert some portion of traffic to farer alternative routes with larger surplus capacities.

By referring the above guidelines and policies for route guidance, we may further demonstrate the practical applications using the test example illustrated in section 4.3 that specific control policies can be implemented accordingly:

(1) Policy 1 is taken for links 1-2, 2-3, 4-5, 7-8, and 12-13.
(2) Policy 2 is taken for links 5-25 and 6-7.
(3) Policy 3 is taken for link 16-17.

5.3 The Operational Process

Even though the proposed model is essentially static, however by employing the L-GP model, one can conduct the following operational process in practical applications in accordance with the change of time-dependent traffic characteristics:

Step 1: Input travel demands and network data.

Step 2: Apply the L-GP method to obtain link volumes, used paths and path flows for each OD pair, generalized travel costs, and queuing delays.

Step 3: Update traffic information concerning traffic congestion and/or incidents for specific links that may have impacts on the entire network.

Step 4: Provide motorists with route guidance instructions and diversion points suggestion.

Step 5: Move to the next bottleneck prediction cycle, update travel demand data, use current traffic conditions as background traffic, and return to step 2.

In light of the above operational process, one can systematically conduct traffic bottleneck predictions and route diversion analysis, and obtain desirable route guidance policies based on potential changes of traffic situations. It is aimed to provide both motorists and highway management agencies with desirable routing suggestions and control polices for on-line traffic management purposes.

6. CONCLUSIONS AND RECOMMENDATIONS

Traffic assignment models are generally employed to the planning levels of transportation systems installation. As an urgent need called for an efficient tool to analyze the short-term traffic distribution patterns, traffic assignment models with on-line update capability are desirable in serving this purpose. In the present research, an operational level of traffic assignment model has been developed to on-line predict traffic bottlenecks for freeway corridors. Unlike the traditional models, the proposed L-GP model explicitly captures roadway's physical property by incorporating link capacity constraints into the optimization problem formulation. Moreover, the generalized travel time function composing of vehicle travel time and link queuing delay is able to foresee the potential occurrence of traffic bottlenecks. Empirical studies based on a local freeway and highway network indicated the capabilities of the proposed model in predicting potential traffic bottlenecks, and their corresponding path travel times and flows. More significantly, desirable traffic control strategies and route guidance policies can be evaluated and provided to motorists in making suitable travel decisions.

The proposed framework has basically presented a desirable mechanism for predicting traffic bottlenecks of freeway corridors. However, from an on-line traffic control perspective, the essential inputs of the proposed model including time-dependent OD demands, free-flow travel times for each link, and information on traffic incidents are difficult to obtained. Therefore, the proposed model is still on the early stage of applications before further solid field test results and data are available. Furthermore, the interaction between the accuracy of traffic bottleneck prediction and the effectiveness of control strategies is also an important topic to be investigated. To test and validate the recommended research topics stated above, a well-designed traffic simulation environment might better serve for these purposes. Future research might also be focusing on the construction of a comparable simulation environment for on-line evaluation purposes.

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NOTATIONS

a	link number
c_{a_0}	free-flow travel time of link a
c_a	travel time of link a
$\breve{c}_a$	generalized travel time of link a
$\hat{c}_a$	extended total travel time of link a
c_p^{rs}	path travel time of p given OD pair rs
$\breve{c}_p^{rs}$	generalized path travel time of p given OD pair rs
CAP_a	link capacity of link a
$\mathbf{d}$	vector of improved directions
d_p^{rs}	improved direction of the p^{th} path given OD pair rs
g_a	link capacity constraints of link a
$\mathbf{h}$	vector of path flow

h_p^{rs}	path flow of p given OD pair rs
i,j	variable i, j
L	Lagrangean function
p	path p
$\hat{p}$	the least distance among paths set
$\overline{q}^{rs}$	traffic demands between OD pair rs
r	origin r
s	destination s
x_a	traffic flow of link a
z	objective function
α	improved pace
β_a	dual variable of link a (queuing delay)
$\overline{\delta}_{ap}^{rs}$	the delta function
ε	the threshold value of convergence
λ	improved pace of the dual variable
$\breve{\pi}^{rs}$	the least generalized travel time between OD pair rs
Ω	feasible solution area
*	the optimal value