DRIVER'S TRAVEL TIME ESTIMATION BY SHOCK WAVE METHOD

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abstract: This paper presents an employment of the shock wave method to estimate travel time for vehicles passing through partial lane closure area. The mathematical formats of the shock wave models were derived basing on the fundamentals of shock wave theory and traffic models from both incident area and freeway work zones. The validation and calibration of the model is based on a field test of four cases. Findings of the study revealed that travel time estimated from the shock wave models were 25.5% more than actually measured for the case with 24 minutes partial lane closure and 14.8% less than actually measured for the case with 10+ hours partial lane closure.

1. INTRODUCTION

The occurrence of incidents such as accidents, vehicle breakdown, and pavement rehabilitation on Taiwan's North/South Freeway (National Sun Yat-Sen Freeway) have seriously plagued this island's intercity transportation which mainly relies on this Freeway. In the past three years, about 25.2 accidents had occurred on this 373.2 kilometer freeway daily(Tsai 1995). Accidents and other forms of incidents have turned traveling on this North/South Freeway a nightmare. Which was so unreliable and unpredictable that a normal four hour travel between Taipei and Tainan might need 8-10 hours if several incidents were encountered during a trip. To illustrate how serious the situation is, the aforementioned frequency of accidents only shares 10.8% of the total number of incidents.(Hwang 1992).

Several remedies have been proposed to countermeasure the occurrence of the incident on the Freeway. Part of them is to reduce the happening of incidents by engineering/enforcement measures. The other part is to lower the impact of incidents by route diversion. Advanced information systems have been considered useful to advise vehicle drivers their incoming travel environment and how to make proper decision if route diversion is possible.

Because traffic behavior on abnormal condition such as lane closure area has been proven different from that on normal condition(Dudek *et al* 1982, Nagui *et al* 1982, FHWA 1983, Hall *et al* 1988, Hwang *et al* 1991, Hwang *et al* 1992), it is difficult to estimate travel time through such a lane closure area by theoretical method or simulation of normal traffic flow. This study thus tried to use shock wave method to develop a model to estimate travel time for such a situation. After model development, four incident on the Sun Yat-Sen Freeway were selected for field test. They were freeway work of reflector replacement and pavement rehabilitation. Time of partial lane closure ranged from 24 minutes to 10+ hours. Findings and comparison of the field test were used for sensitivity analysis.

2. SHOCK WAVE THEORY

As early as 1955, researchers had used the concept of fluid mechanism to model the traffic flow(Lighthill *et al* 1955). From then to 1980, before microscopic traffic simulation models were popularly used, many shock wave theories, models, and applications had been developed(Rorbech 1968, Wirasinghe 1978, Avishai 1980, Kuhne 1984). Of them the most famous one was the paper of "On kinematic waves: II. A theory of traffic flow on long crowded roads" written by Lighthill and Whitham(Lighthill *et al* 1955). In which they discussed the application of fluid mechanism to model the traffic flow and was reprinted in HRB Special Report 79 in 1964(Gerlough *et al* 1975).

A shock wave is defined as the motion or propagation of a change in concentration and flow. Figure 1 illustrated the formation of a shock wave. When traffic flow from concentration $\mathbf{K_b}$, volume $\mathbf{Q_b}$, and speed $\mathbf{U_b}$ changes into the situation of $\mathbf{K_a}$, $\mathbf{Q_a}$, and $\mathbf{U_a}$, there forms a backward shock wave with speed $\mathbf{W_{ab}}$.

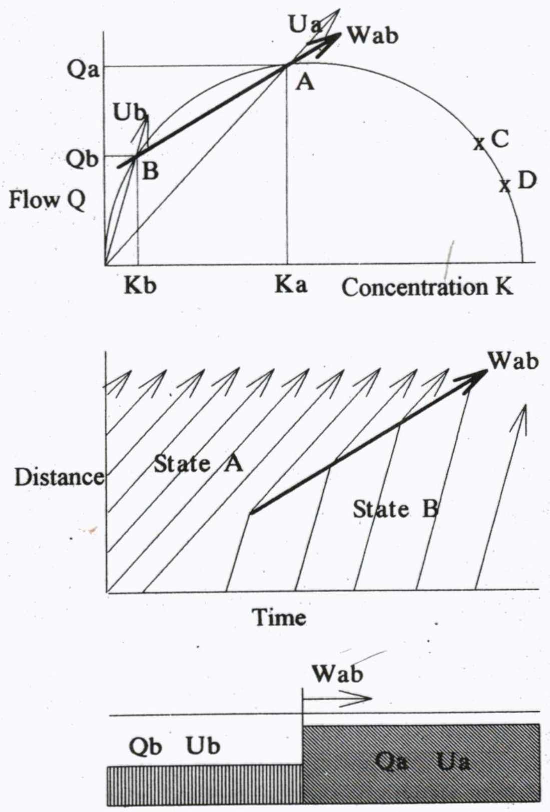


Figure 1. Shock Wave Basic Form

There are many possible causes in traffic flow which might form a shock wave. Table 1 summaries the six types of shock wave and their phenomena in a traffic flow:

Table 1. Type and Formation of Shock Wave

Type	Phenomenon and Cause
frontal stationary	occur at the entry point of the bottleneck, but congestion does not progress upstream for demand less than capacity
backward forming	congestion progress upstream when travel demand is greater than capacity
forward recovery	shock wave moves downstream and gradually disappears when travel demand decreases after congestion occurs
rear stationary	beyond the bottleneck, shock wave move downstream
backward recovery	the congestion disappears in upstream direction when the cause of congestion disappears
forward forming	traffic blocked by slow moving vehicle and can't make lane change, forms platoon, shock wave, and move downstream

When shock wave theory is applied, there are assumptions and restrictions as follows.

- capacity remain constant when a set of parameters are used
- presérvation of flow, one entry and one exit
- flow change instantly from one form to another such as Figure 1 shows
- no stochastic phenomenon is considered
- speed changes only at the interface of two flow and occurs instantly with no acceleration and deceleration considered
- no occurrence of secondary incident.

Three steps were followed in this study to develop a shock wave model and to use it for travel time estimation.

1. select a flow, concentration, and speed relationship
2. measure upstream/downstream flow to compute shock wave speed
3. plot the time space diagram and calculate the path travel time

Table 2 presents the single regime macroscopic models developed in the past(Greenshields 1934, Greenburg 1959, Underwood 1961, Drake *et al* 1967, Drew 1968). There were also researchers who developed traffic models by application of the microscopic traffic simulation. May, Keller, Gazis, *et al*, had developed the M-L matrix model (Table 3)(Gazis *et al* 1961, May *et al* 1967) by General Motor's microscopic simulation model(Pipes 1976). It was also proven that the single regime macroscopic models in Table 2 can be derived through the M-L model of Table 3. In which the variables M and L are related to a driver's perception and reaction in formula (6) and (7). M represents the exponent of travel speed and L represents the exponent of vehicle headway, λ is the sensitivity of vehicle maneuver which has a positive relationship with travel speed and an inverse relationship with vehicle headway. α is a constant.

Table 2. Single Regime Traffic Flow Model

Time	Developer	Formula	Explanation
1934	Greenshields	$U = U_f - \left(\frac{U_f}{Kj}\right)K$ (1)	U_f: Free Flow Speed
1959	Greenberg	$U = U_o \times Ln\left(\frac{K_j}{K}\right)$ (2)	K_j: Congestion Concentration
1961	Underwood	$U = U_f \times e^{-\left(\frac{k}{k_o}\right)}$ (3)	U_o: Speed at Maximum Flow
1967	Drake *et al*	$U = U_f \times e^{-\frac{1}{2}\left(\frac{k}{k_o}\right)^2}$ (4)	K_o: Concentration at Maximum Flow
1968	Drew	$U = U_f \times \left[1 - \left(\frac{K}{K_j}\right)^{\frac{n+1}{2}}\right]$ (5)	U: Speed K: Concentration

Table 3. *M-L* Traffic Flow Model Matrix

	$M<1$	$M=1$	$M>1$
$L<1$	$\left(\frac{U}{U_m}\right)^{1-M} = \left(\frac{L-M}{L-1}\right)\left[1-\left(\frac{K}{K_j}\right)^{L-1}\right]$	Models in this region do not exist for they do not meet requirements of travel margin condition.	
$L=1$	$\left(\frac{U}{U_m}\right)^{1-M} = (1-M)Ln\frac{K_j}{K}$		
$L>1$	$\left(\frac{U}{U_f}\right)^{1-M} = \left[1-\left(\frac{K}{K_j}\right)^{L-1}\right]$	$Ln\frac{U}{U_f} = \left(\frac{1}{1-L}\right)\left(\frac{K}{K_m}\right)^{L-1}$	$\left(\frac{U}{U_f}\right)^{1-M} = 1-\left(\frac{1-M}{L-M}\right)\left(\frac{K}{K_m}\right)^{L-1}$

$$A_{n+1}(T+t) = \lambda\left[U_n(T) - U_{n+1}(T)\right] \tag{6}$$

$$A_{n+1}(T+t) = \alpha\frac{(U_{n+1})^M}{(X_n - X_{n+1})^L}\left[U_n(T) - U_{n+1}(T)\right] \tag{7}$$

where $A_{n+1}(T+t)$: acceleration of vehicle n+1 at time T+t
$U_{n+1}(T)$: speed of vehicle n+1 at time T

3. MODEL DEVELOPMENT

To develop the shock wave model, it is necessary to choose a basic form of traffic model for employment which would suit the traffic behavior on Sun Yat-Sen Freeway. This study choose Mr. Lin's model (Lin 1987) as the basic format. The model is an application of the M-L matrix method (Table 3) and is a two regime fitted model instead of a single regime model as those in Table 2. The model (illustrated in Table 4) has both forms for non-congested flow ($M \geq 1$ *and* $L \geq 1$) and congested flow ($M < 1$ *and* $L \leq 1$) and is used to describe traffic behavior at area without partial lane closure.

After the model format was selected (Table 4), the freeway capacity values of partial lane closure area need to be known for model application. Those data from the author's past researches were input into the model(Hwang *et al* 1991, Hwang *et al* 1992). The speed of shock wave and travel time through an incident area can then be computed.

Table 4. Traffic Model of the Study

Model (Non-congested Flow)	
M,L Values	L=5.12 M=4.70
Other Parameters of the Model	Q_m=2,390 veh/hr U_m=57 km/hr K_m=42 veh/km
$U = 105.9\left(1 + 8.81\left(\frac{K}{41.9}\right)^{4.12}\right)^{-0.27}$	
Model (Congested Flow)	
M,L Values	L=1 M=0.086
Other Parameters of the Model	Q_m=1,860 veh/hr U_m=40 km/hr K_m=46.5 veh/km
$U = \left(26.6 Ln\frac{138.9}{K}\right)^{1.094}$	

Table 5. Capacity at Partial Lane Closure Area

Accident Type Incidents				
Original Lane No.	Lane Closed	Capacity PCPHPL	Capacity Left PCPHPL	Capacity Reduced (%)
2	1	1810	1810	51.3
2	shoulder	1730	3460	7.0
3	2	1715	1715	69.3
3	1	1577	3154	43.5
4	3	1652	1652	77.8
4	2	1527	3054	59.0
4	1	1608	4824	35.2
Construction Type Incident				
2	1	1575	1575	57.7
4	i	2160	6480	12.9
4	2	2020	4040	45.7

Note: Capacity reduced = (lane no. x 1860 - capacity left)/(lane no. x 1860)

3.1. Travel Time Estimation by Static Method

There are two approaches to estimate vehicle travel time going through an incident area by the developed shock wave model. The first one assumes the upstream traffic demand remains constant after the occurrence of an incident. Travel time is estimated by a static method. The second one considers the variation of upstream traffic. Keeping track of the flow change becomes a necessity and an integral dynamic approach is used. To describe those mathematical formats to compute vehicle travel time in a shock wave, Table 6 summarizes the conditions and formulas to be employed in the static model. There are a total of nine possible conditions to decide which passage a vehicle will follow in condition of a shock wave. For each passage, it is broken down to 1-4 sub passages for computation of vehicle travel time. Figure 2 and Figure 3 illustrate the conceptual passages for those nine passages. Because the derivation of those nine conditions and formulas is very lengthy, it is not included in this paper.

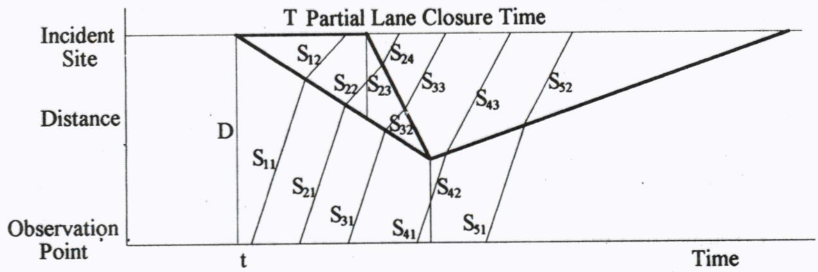


Figure 2. Travel Passages when Observation Point is beyond Congestion

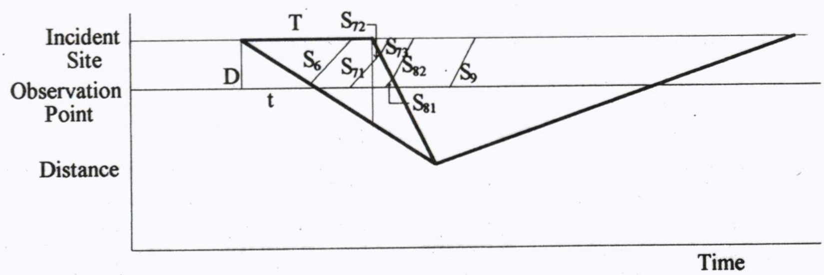


Figure 3. Travel Passages when Observation Point is within Congestion

3.2. Travel Time Estimation by Dynamic Method

The dynamic approach is to allow the incoming traffic volume to be updated in the shock wave model when vehicle travel time is estimated. Of the various combinations might be considered for employment of the dynamic approach, this research emphasizes on two situations. They are: 1. short term lane closure in which incident clearance time is considered, and 2. long term lane closure in which incident clearance time is ignored.

1. short term lane closure

At short term lane closure, the shock wave formulas to estimate vehicle travel time are the same as those in Table 6. The only difference is the upstream traffic must be updated and the shock wave W_1 and W_2 be modified accordingly. In the mean time the partial lane closure time T and the measuring distance D are two other independent variables could be changed when vehicle travel time is computed. For such a process, an integration is needed and formula (8) is used to perform such an integration.

$$\int (W_{11} + W_{12} + \dots\dots\dots + W_{1n-1})\Delta t = L \tag{8}$$

Where W_{1n} is the shock wave for vehicle 1 at time n, and L is the accumulation of travel distance of vehicle 1

2. long term lane closure

When incident clearance time is not considered as a variable in a long term incident, which assumes $T \Rightarrow \infty$, such as a freeway construction work. The emphasize of the analysis is to study the impact of the change of traffic flow on travel time. The passages of the vehicle can be categorized into two forms.

(1). When $|W_1\Delta t + \dots\dots\dots + W_{n-1}\Delta t_{n-1}| < D$, which means a vehicle encountering the shock wave after passing the observation point, the S_1 passage of Figure 2 should be followed and formulas (9) and (10) used to calculate vehicle travel time and distance.

$$S_{11} = \frac{D + (W_1\Delta t_1 + \dots\dots\dots + W_{n-1}\Delta t_{n-1})}{U_1 - W_n} \tag{9}$$

$$S_{12} = \frac{-(W_1\Delta t_1 + \dots\dots\dots + W_{n-1}\Delta t_{n-1} + W_n S_{11})}{U_2} \tag{10}$$

$$S_1 = S_{11} + S_{12}$$

Δt : time interval to update traffic flow

$W_1 \dots\dots W_n$: shock wave speed by traffic flow

(2). When $|W_1\Delta t + \dots\dots\dots + W_{n-1}\Delta t_{n-1}| \geq D$, which means a vehicle encountering the shock wave before passing the observation point, the S_2 passage of Figure 2 should be followed and formula (11) is employed.

$$S_2 = \frac{D}{U_2} \tag{11}$$

3. when lane closure time T is unknown

When lane closure time T is unknown, application of the shock wave model to estimate vehicle travel time becomes very complicated. It has to be clarified if the lane closure situation had ended at the beginning of each dynamic computing interval. A deterministic simulation model which uses the shock wave model for its inherent logic may prove useful in this topic. The model develop for this research can only conduct sensitivity analysis for the condition when lane closure time T is unknown.

Table 6. Vehicle Time-Space Passage Formula

Condition	Path	Formula to Calculate Passage Travel Time		
$t+S_{11}+S_{12}<T$	S_1	$S_{11}=\dfrac{D-\lvert W_1\rvert t}{\lvert W_1\rvert+U_1}$	$S_{12}=\dfrac{\lvert W_1\rvert(t+S_{11})}{U_2}$	$S_1=S_{11}+S_{12}$
$t+S_{11}+S_{12}\geqq T$ 且 $t+S_{11}<T$	S_2	$S_{21}=\dfrac{D-\lvert W_1\rvert t}{\lvert W_1\rvert+U_1}$ $S_{24}=\dfrac{\lvert W_2\rvert S_{23}}{U_3}$	$S_{22}=T-t-S_{21}$ $S_2=S_{21}+S_{22}+S_{23}+S_{24}$	$S_{23}=\dfrac{\lvert W_1\rvert(t+S_{21})-U_2S_{22}}{U_2+\lvert W_1\rvert}$
$t+S_{31}\geqq T$ and $t+S_{3i}+S_{32}\leqq T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}$	S_3	$S_{31}=\dfrac{D-\lvert W_1\rvert t}{\lvert W_1\rvert+U_1}$ $S_3=S_{31}+S_{32}+S_{33}$	$S_{32}=\dfrac{D-\lvert W_2\rvert(t+S_{31}-T)-U_1S_{31}}{U_2+\lvert W_2\rvert}$	$S_{33}=\dfrac{\lvert W_2\rvert(S_{32}+S_{31}+t-T)}{U_3}$
$U_1S_{41}<D-\lvert W_1\rvert\times\left(\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}+T\right)$	S_4	$S_{41}=T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}-t$ $S_4=S_{41}+S_{42}+S_{43}$	$S_{42}=\dfrac{D-\lvert W_1\rvert\left(T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}\right)-U_1S_{41}}{U_1-W_3}$	$S_{43}=\dfrac{D-U_1(S_{41}+S_{42})}{U_3}$
$t>T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}$	S_5	$S_{51}=\dfrac{D-\lvert W_1\rvert\left(T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}\right)+W_3\left(t-T-\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}\right)}{U_1-W_3}$		$S_{52}=\dfrac{D-U_1S_{51}}{U_3}$ $S_5=S_{51}+S_{52}$
$t>\dfrac{D}{\lvert W1\rvert},t+S_6\leq T$ $D<\lvert W1\rvert\left(T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}\right)$	S_6	$S_6=\dfrac{D}{U_2}$		
$t+S_6>T,t<T,$ $D<\lvert W_1\rvert\left(T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}\right)$	S_7	$S_{71}=T-t$ $S_7=S_{71}+S_{72}+S_{73}$	$S_{72}=\dfrac{D-U_2S_{71}}{\lvert W_2\rvert+U_2}$	$S_{73}=\dfrac{D-U_2(S_{71}+S_{72})}{U_3}$
$t>T,t<T+\dfrac{D}{\lvert W_2\rvert},$ $D<\lvert W_1\rvert\left(T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}\right)$	S_8	$S_{81}=\dfrac{D-\lvert W_2\rvert(t-T)}{\lvert W_2\rvert+U_2}$	$S_{82}=\dfrac{D-U_2S_{81}}{U_3}$	$S_8=S_{81}+S_{82}$
$t\geq T+\dfrac{D}{\lvert W_2\rvert},$ $D<\lvert W_1\rvert\left(T+\dfrac{T\lvert W_1\rvert}{\lvert W_2\rvert-\lvert W_1\rvert}\right)$	S_9	$S_9=\dfrac{D}{U_3}$		

S: time to travel the path, D: distance between incident site and observation point

T: partial lane closure time, t: time difference between vehicle passing the observation point and the start of partial lane closure, W_1,W_2,W_3:shock wave speed, U_1,U_2,U_3:traffic flow speed

4. MODEL VALIDATION AND SENSITIVITY ANALYSIS

This section of the paper discusses validation of the developed shock wave model and findings of the field test as well. Since it is difficult to predict occurrence of an accident and to arrange its survey accordingly, validation of the model relies mainly on construction type incident. For complexity of the multiple shock wave considered, only the shock wave in transition of two flows were evaluated. For the field test a total of 180-minute travel data were collected as presented in Table 7. Two types of lane closure were included in the surveys. They were median lane and shoulder lane/shoulder closed. The road types studied included four lanes and six lanes freeway. The partial lane closure time ranged from 24 minutes to more than 10 hours.

Table 7. Survey Field Situation

Survey No.	Type	Lane Closed	Closed for	Type of Work	Survey Time
1	2 Lanes	median lane	24 min.	Lane Marker Replacement	30 minutes
2	2 Lanes	median lane	43 min.	Lane Marker Replacement	50 minutes
3	3 Lanes	shoulder lane and shoulder	36 min.	Lane Marker Replacement	40 minutes
4	2 Lanes	shoulder lane and shoulder	10+hours	Pavement Rehabilitation	60 minutes

4.1. Field Survey

During the survey, a four men team was placed along an incident. Their positions were shown in Figure 4. The license plate method which records the number of a license was used to trace the movement of vehicles. Traffic volume was counted and reported once per minute.

Because traffic volume is an input to the model for vehicle travel time estimation, those vehicles passing the observation point had to be counted. This research classified the vehicle in two categories to simplify the survey process. Vehicle classification was either 1. passenger vehicle and pickup truck, or 2. heavy vehicle such as bus, truck, and combination vehicle. Table 8 lists the passenger car equivalents used by the study to covert traffic count into hourly passenger car volume(Hwang *et al* 1992). Because it is almost impossible to trace the movements of all vehicles, the following priorities were used to selected vehicle to be traced. The priorities were 1st. buses or yellow cab, 2nd. white-color passenger vehicles, and 3. red-color passenger vehicles.

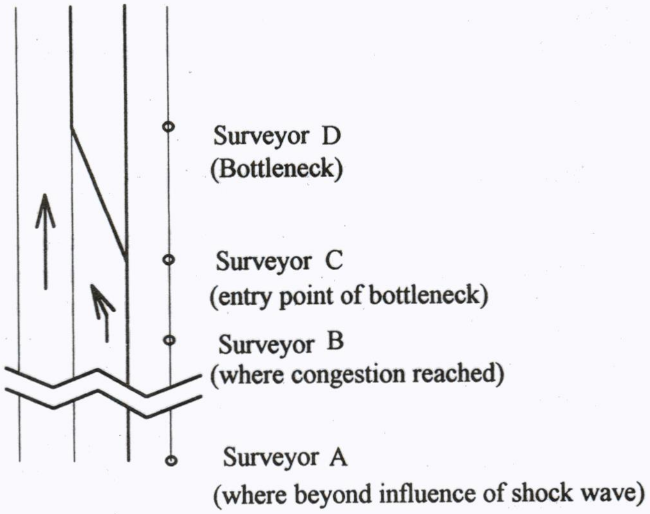


Figure 4. Placement of Surveyors

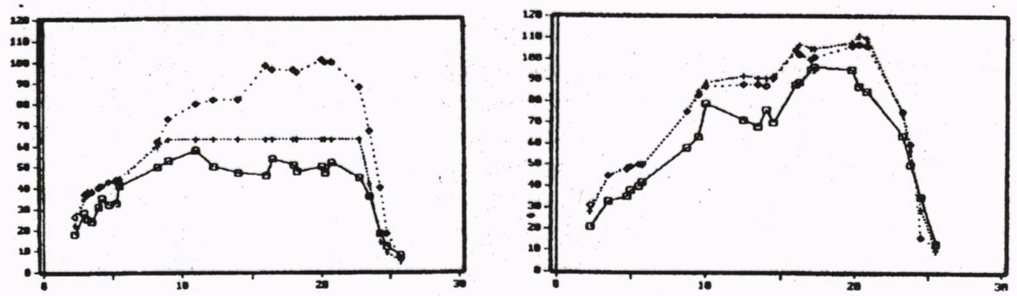
Table 8. Passenger Car Equivalents at Work Zone Area

% of heavy veh.	10	20	30	40
PCE	1.7	1.5	1.4	1.4

4.2. Comparison between Observation and Model

4.2.1. Comparison with Queueing Model

In depicting transition of traffic flows, both shock wave model and queueing model can be derived from the static models as in Tables 2 or 3. The shock wave model considers the motion of a change in concentration. However, the queueing model piles up the arriving vehicles vertically. No form of wave is considered. In order to learn their difference, traffic flow from the first survey was used to estimate travel time by both shock wave model and queueing model. The results and the observed values are presented in Figure 5. It is seen from Figure 5a that the output from the queueing model is significantly different from that of the shock wave model and the real situation. A thorough investigation revealed that when measuring distance was 150 meters (D's value on Figure 3 or the distance between B and D on Figure 4) , the road section of BD got fully congested at 17 minutes. Before then, the predictions of travel time from both queueing model and shock wave model were close to each other. However, after the congestion at 17 minutes, queueing model overestimated travel time significantly till the end of lane closure (23 minutes). The phenomenon is explained that traffic behavior is more like a form of wave which will adjust to the travel condition gradually instead of stopping abruptly. When the observation point was 300 meters upstream from the bottleneck and got no congestion there (D's value on Figure 2, or the distance between A and D on Figure 4), both queueing model and shock wave model provide relatively close travel time to the observed values.



150 meters 300 meters

□ : observed, + : shock wave model, ◇ : queueing model

y-axis: section travel time(unit: seconds), x-axis: time of observation(unit: minutes)

Figure 5. Comparison of First Survey Result by Two Models

4.2.2. Travel Time Sensitivity Analysis

From the discussion above, there are several variables which might affect the estimate of vehicle travel time. They are 1. distance of travel, 2. time of observation, 3. frequency of flow update, and 4. the lane which is closed. It is interesting to know how the four factors affect the performance of the model. Therefore, vehicle travel time estimations of the four surveys were used to plot Figures 6-9 as well as the preparation of Tables 9-12. Sensitivity analysis were then conducted.

1) Travel Distance

From Tables 9-12, the comparison between estimated travel times and those observation values, it is seen that when travel distance is larger, deviation from observation tends to decrease. It may be explained by Figures 6a & 7a that the shock wave method provides only one travel time during the congestion period which is the straight line segment in the plot. The model does not tend to explain the speed variation within group. However, individual vehicle might move faster or slower instead of a constant speed.

2) Time of Observation

It is seen from all the figures that estimations of vehicle travel time at the beginning or end of a congestion provide better fitting to observed values. During the congestion period, the estimations deviate more from the observed value than those from the transition period. After thorough investigation of the data, it is learned that during the congestion period there were stop-and-go traffic behavior which was unable to be described by the shock wave theory for which assumes the traffic flow is a continuous fluid. Nevertheless, plot of the data still supports the conclusion that the model suits well the description of traffic behavior during the flow transition period.

3) Volume Update Frequency

During a congestion period, the upstream incoming traffic might change from time to time. It may be necessary to update traffic flow to better estimate vehicle travel time. However, it is not known how often the traffic flow has to be updated. Theoretically, the deviation from model estimations to observed values should be reduced if traffic flow is updated more frequently. However, the results of comparison from most of figures and tables do not support such an hypothesis. Only some clues exist to support such a thinking. One of the clues occurs at part b of the no. 1 and 2 plots of the first survey which a 300 meter travel distance was used. The shapes of the two curves fit better when flow was updated once every minute or two minutes. On the contrary, there are also evidences to disapprove such a hypothesis. The plot of the third survey shows that the estimation curve fits better when flow is less frequently updated. No consistent conclusion can be reached. The cause of such a phenomenon was studied in detail and it was again attributed to the "stop-and-go" traffic behavior. Because the shock wave model is unable to depict the stop-and-go phenomenon, it has no advantages to update traffic flow frequently during a bumper to bumper travel condition.

4) Lane Closure Position

There were two types of lane closure in the four surveys. The first and second surveys had median lane closed. The third and the fourth survey had both the shoulder lane and shoulder closed. Tables 9-12 illustrate that the deviation percentages of the third and fourth surveys are less than those of the first and the second surveys. In addition, the plot of the fourth survey presents an interesting phenomenon that the observed vehicle travel times are higher than those estimated. Analysis of the field situation reveals that such a result is related to the violation of shoulder use. During the first and the second surveys, some vehicles illegally used the shoulder to travel which reduced the number of vehicles waiting to pass the incident area and affected the travel time surveyed. For it was unknown how much the freeway capacity would be affected when shoulder was only occasionally used, vehicle travel time estimations by a model which neglected such a phenomenon surely would be higher than those observed.

Table 9. Mean Deviation of the First Survey (%)

Sample Size	Measure Distance	Flow Update Frequency					Mean Deviation
		1 min.	2 min.	3 min.	4 min.	5 min.	
26	150 m	28.50	25.03	30.00	27.32	23.08	26.79
23	300 m	24.50	21.97	26.29	26.91	21.06	24.15

Table 10. Mean Deviation of the Second Survey (%)

Sample Size	Measure Distance	Flow Update Frequency					Mean Deviation
		1 min.	2 min.	3 min.	4 min.	5 min.	
41	200 m	23.44	22.57	22.53	22.45	22.80	22.76
44	400 m	21.46	19.86	17.09	17.95	19.40	19.55
43	600 m	20.02	17.09	17.90	15.78	16.43	17.45

Table 11. Mean Deviation of the Third Survey (%)

Sample Size	Measure Distance	Flow Update Frequency					Mean Deviation
		1 min.	2 min.	3 min.	4 min.	5 min.	
34	200 m	18.78	22.22	24.17	17.60	-9.24	14.70
54	400 m	18.77	21.22	20.74	18.23	-11.12	13.57

Table 12. Mean Deviation of the Fourth Survey (%)

Sample Size	Measure Distance	Flow Update Frequency 1 min.	2 min.	3 min.	4 min.	5 min.	Mean Deviation
53	400 m	-12.81	-13.26	-16.34	-16.02	-14.28	-14.54
54	800 m	-12.29	-12.95	-17.06	-17.28	-15.53	-15.02

5. CONCLUSION AND RECOMMENDATION

This study employed the shock wave theory and the M-L matrix traffic models to develop a method to estimate vehicle travel time through an incident area where part of freeway was blocked. Several conclusion and recommendation could be reached. They are

1. The shock wave model is able to describe the traffic behavior in transition of flow changes. It is unable to describe the "stop-and-go" bump to bump congested traffic condition. Field test of the model shows that some deviations ranging from 5-25 seconds (9.24-30.00%) are observed which may not be significant in real world traveling.

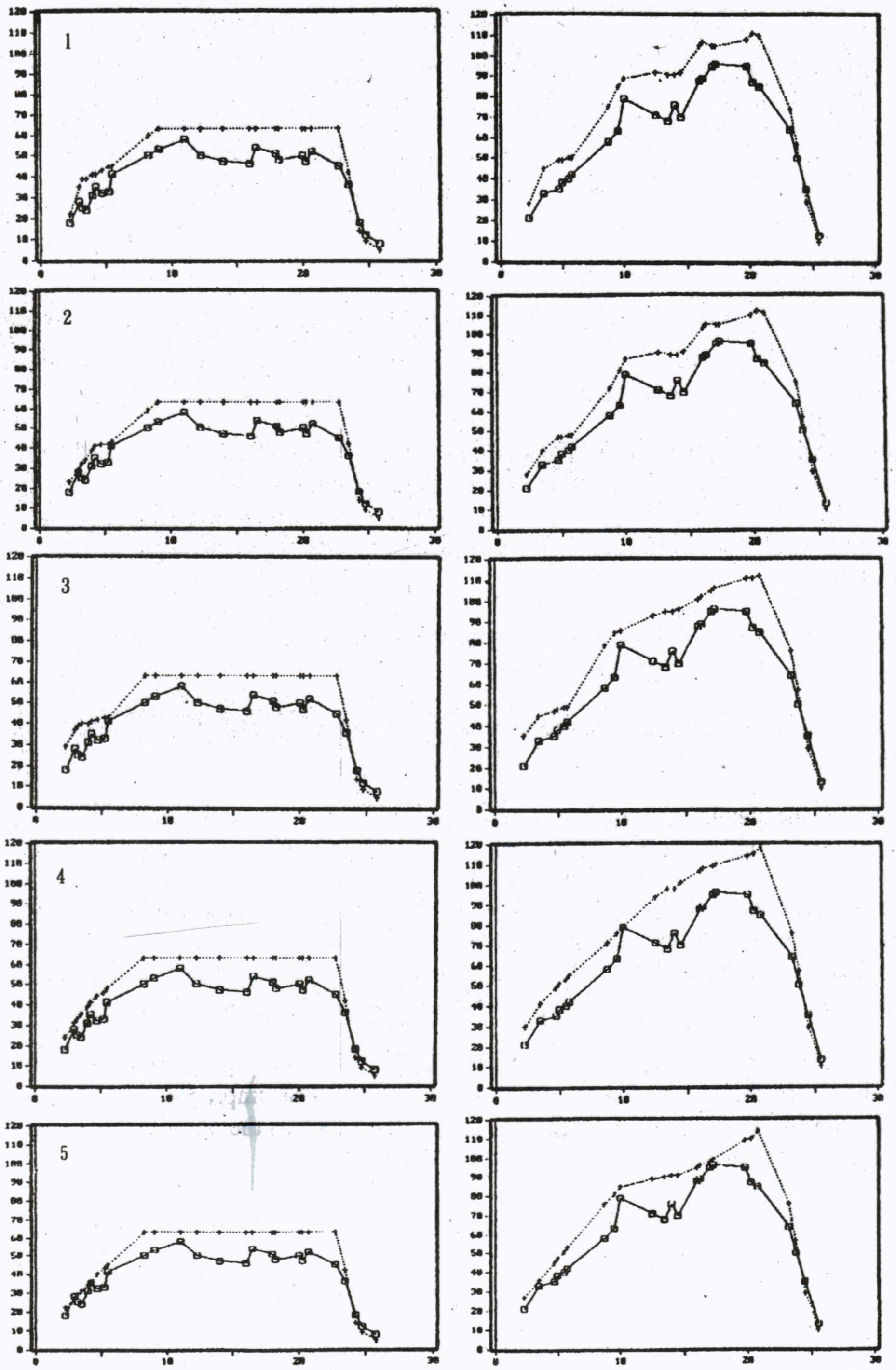
2. The shock wave model can predict travel time more accurately than queueing model at the area of incident which is congested.

3. Field test shows that the developed shock wave model is more dependable if the distance to measure travel time is larger.

4. Because the shock wave model is unable to describe the "stop-and-go" traffic situation, frequency to update traffic volume is insignificant from one to five minutes.

5. Analysis of the study reveals that when shoulder may be occasionally illegally used, travel time estimations will overestimate the real values. Field test shows the average deviation is 22.16%. If no violation is observed, travel time estimation is close to the observation values. The field test shows an average deviation of only -0.26%.

6. The "Stop-and-Go" situation of in congested traffic flow is very difficult to model with a simple mathematical format. This study found it was improper to depict such a behavior in shock wave theory. Some other method such as the microscopic simulation may be useful to analyze the "Stop-and-Go" behavior.

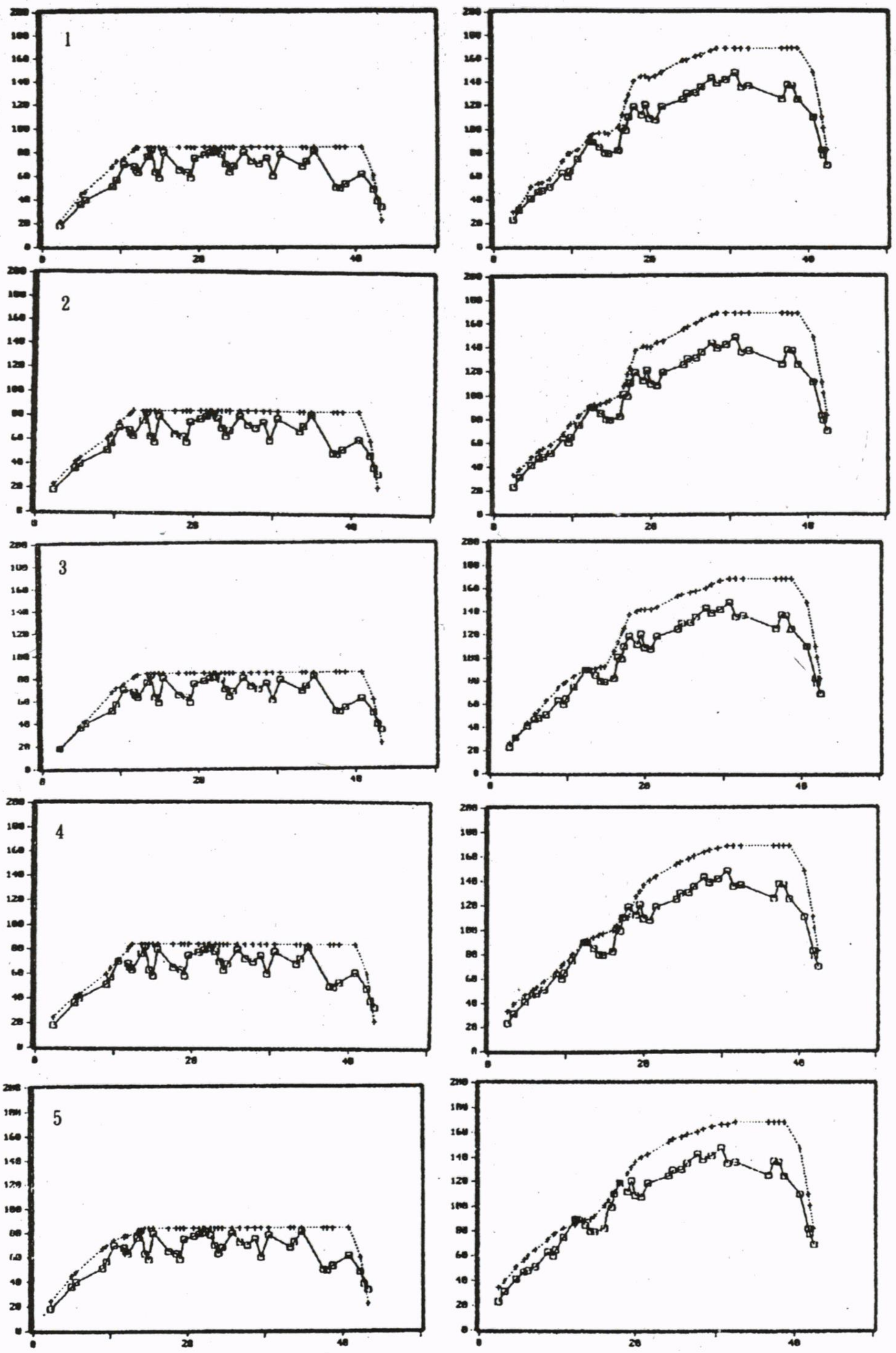


150 meters 300 meters

□: observed, +: shock wave model

y-axis: section travel time (unit: seconds), x-axis: time of observation (unit: minutes)

Figure 6. Comparison of First Survey (Partial Lane Closure 24 minutes)

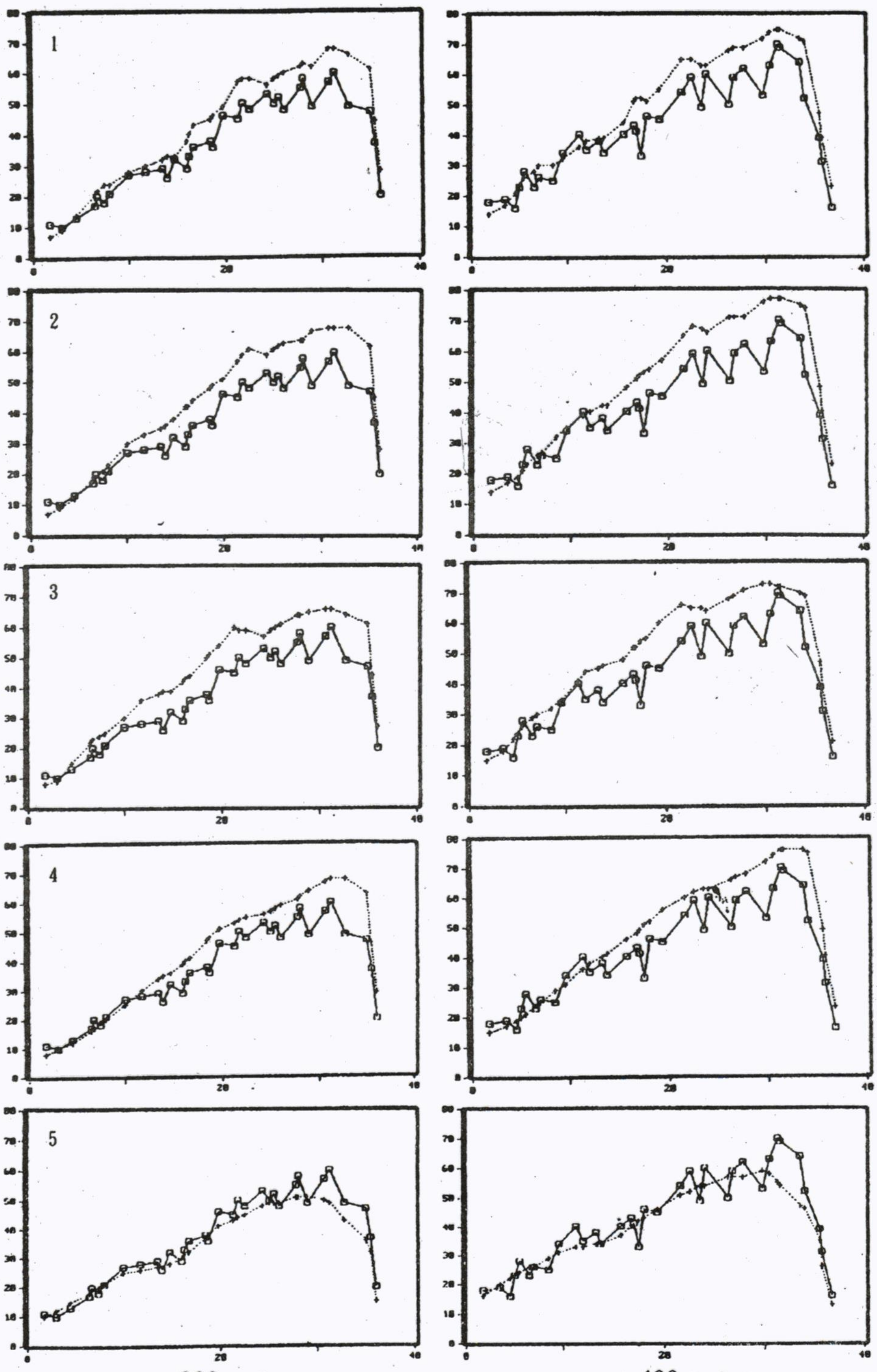


200 meters 400 meters

□: observed, +: shock wave model

y-axis: section travel time (unit: seconds), x-axis: time of observation (unit: minutes)

Figure 7. Comparison of Second Survey (Partial Lane Closure 43 minutes)

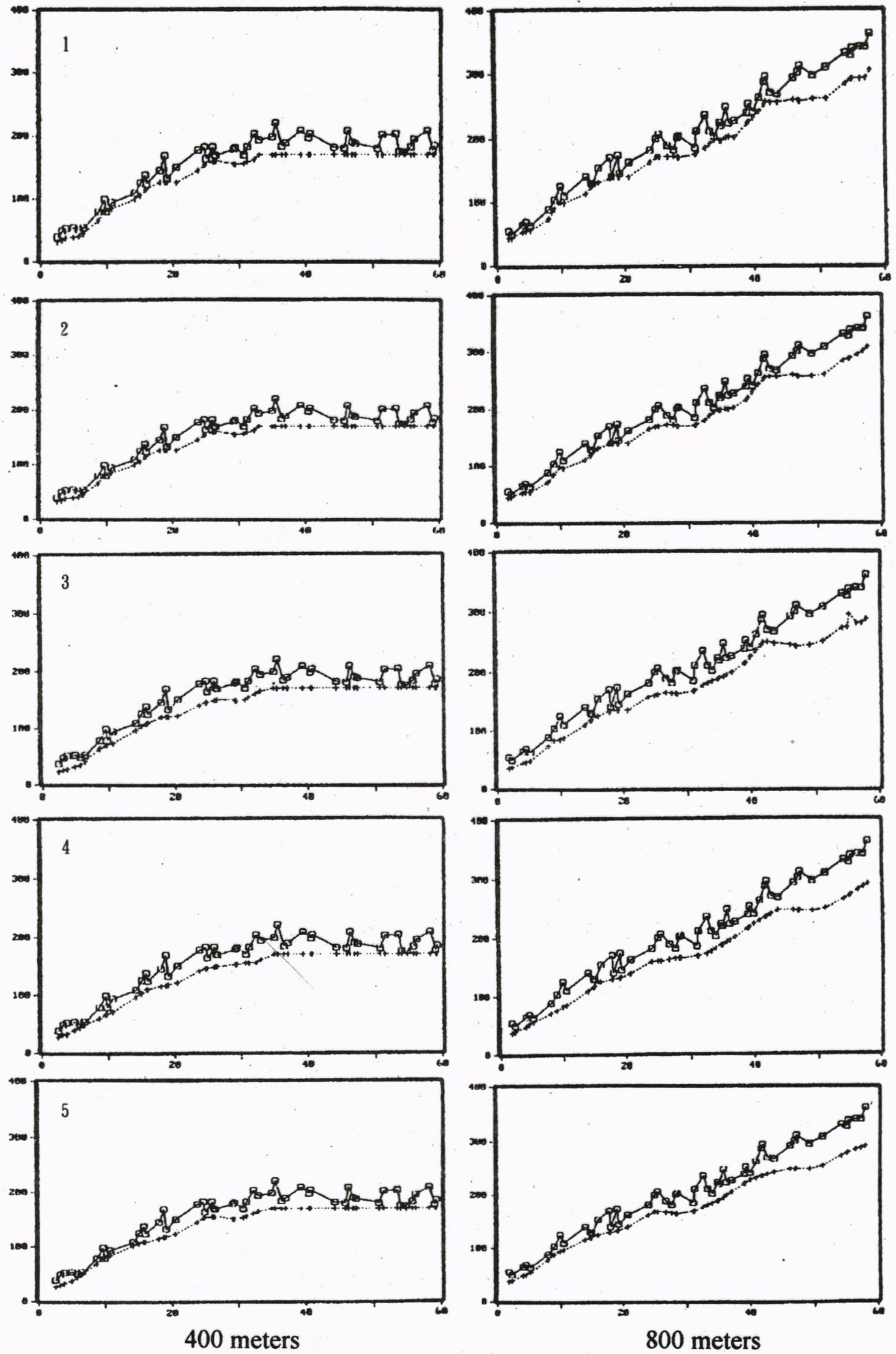


200 meters 400 meters

□: observed, +: shock wave model

y-axis: section travel time (unit: seconds), x-axis: time of observation (unit: minutes)

Figure 8. Comparison of Third Survey (Partial Lane Closure 36 minutes)



y-axis: section travel time (unit: seconds), x-axis: time of observation (unit: minutes)

Figure 9. Comparison of Fourth Survey (Partial Lane Closure 10+hours)

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