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Research Article

Extent of Priority Stream Delays at Midblock Median Opening Zone

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Abstract: The study is concerned with investigating delays and queues in both flow directions of exclusive U-turn median openings zone. Note that other turning movements are not allowed at exclusive U-turn median openings zone. Travel time delay study was carried out at four sites in Johor, Malaysia. Resultsshow that average delay of 5s can be expected at divergingsection and no significant delay to conflicting traffic flows at the merging section. Delayswere recorded for vehicles waiting to merge at the exit lane. The paper concluded that weaving may be called to account for travel time delay at the diverging section. And also that since vehicle at the merging section must give way, there will be no delay to conflicting traffic flow.

Keywords: Delay, diverging, flow, merging, median opening, speed, travel time, U-turn

INTRODUCTION

Midblock U-turn facilities at signalised and priority intersections are very commonly found along federal highways in Malaysia. Over the past few decades, the use of U-turn median openings has been intensified. Median openings at commonly found along multilane highways in Malaysia; they are often built as direct or indirect U-turn midblock facilities with single entry and exit lane, IDRA Road layout Design (2011). Since Malaysia drive on the left hand side, it is conventional wisdom that motorist turn right at median opening. Motorists are also expected to travel faster when overtaking on right lane. However, the introduction of midblock U-turn facilities along roadway segments has provoked fierce national debates about their benefits and risks. Often U-turn traffic movements at roadway segments are channelized and aided with splitting islands so that drivers can be on their desired trajectories. Drivers will have to keep to the right lane; decelerate when diverging, accelerate when converging. These dangerous manoeuvres beg the question; ‘what are the induced traffic flow consequences when the lead vehicle decelerates or accelerates abruptly?

Median openings are effective conflict-points reduction mechanism (TRB (Transportation Research Board), 1997) because they allow vehicles to make U-turn at segments thereby avoiding immediate intersection that could be laden with many conflict points. In Malaysia, some midblock u-turning facilities are built as complimentary facilities to existing infrastructure design, others are built as a complete replacement to existing facilities on the premises that they will reduce conflicts and ease congestion at adjoining intersections. The issue of open midblock u-turning facilities has provoked fierce national debates among road providers and users in Malaysia. Argumentshavebeenadvancedbysome opponents of infrastructure modification projects that the increased numbers of u-turning facilities may compromise safety and exacerbate operational problems affected roadway. As contained many literatures (TRB (Transportation Research Board), 1997), U-turn midblock facilities are effective conflict-points reduction mechanism. What about travel time delays and weaving intensity induced by these midblock facilities? Can they be offset against conflict-points reduction at intersection? Therefore, it is not surprising that the issue of midblock u-turning facilities along a roadway segment has provoked fierce national debates in Malaysia.

Malaysia consists of thirteen states and three federal territories and has a total landmass of 329,847m^2 separated by the South China Sea into two similarly sized regions, Peninsular Malaysia and Malaysian Borneo (IDRA Road layout Design, 2011). Malaysian highways are classified as expressway, federal, state, municipal highways and others. Midblock facilities are placed on multilane federal highways. Federal Highways are often built with 2 carriageway lanes in each direction with imposed speed limit of 90km/h. Since Malaysia motorists observe the left hand drive rule, it is conventional wisdom that motorists are expected to travel faster when overtaking on right lane. However, it is unwise to overtake at median opening zones because of the risks associated with weaving intensity at the median opening zones. Weaving intensity can lead to travel time delays at the median opening zones. In previous studies, flow rate contraction and weaving intensity have been identified as significant only at the entry section of U-turn median opening zone. That being the case, it can be postulated that traffic perturbations and their resultant travel time

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delay will also be more prominent at the entry than the exit section of the median opening zone. The objectives are to compute and compare travel time delays associated with merging and diverging zones of the midblock facilities.

MATERIALS AND METHODS

Travel time delay is taken as the difference between the actual time required to traverse a road section and the time corresponding to the average speed under free-flow condition. It includes acceleration and deceleration delay in addition to stopped delay. The US Bureau of Public Records-BPR (1964) uses Eq.(1) below when predicting travel time over length of roadway. So there is no need to model a new travel time, what is needed is modification of the equation to reflect new constraints arising from median openings:

$$T = t_f\left\{1 + a\left(\frac{v}{Q}\right)^b\right\} \quad (1)$$

where,
T :Predicted travel time over length of roadway
v :Traffic volume
t_f :Travel time at free flow speed
Q :Capacity
a :Ratio of t_f to the speed at capacity
b :Abruptness ofcurve drops from t_f

According to Highway Capacity Manual (HCM) (2010), a high value of *b* causes speed to be insensitive to *v/Q* until *v/Q* gets close to 1.0; then the speed drops abruptly. Dowling *etal*. (1998) evaluated the standard BPR curve against more recent speed-flow data and concluded that the BPR curve underestimated speeds at v/c ratios between 0.80 and 1.00 and overestimated speeds in queuing conditions (when the demand exceeds capacity). They refitted the BRP equation to the motorway speed-flow curves and recommended that 'a' = 0.20 and 'b' = 10. Dowling *et al*. (1998) recommended updated BPR speed/flow curves for motorway links to improve the accuracy of speed estimates used in transportation demand models. These updated curves generally involved the use of higher power functions that show relatively little sensitivity to volume changes until demand exceeds capacity, when the predicted speed drops abruptly to a very low value. The updated BPR curves have 'a' parameters that vary from 0 to 1.0 and 'b' parameters that vary from 4 to 11. In any case BPR speed-curve has been validated against speed/flow data for both uninterrupted and interrupted flow facilities and could be useful in predicting travel time. Since the study is interested in predicting travel time where v/c <0.90, the then a = 0.20 and b = 10. If the coefficients are plugged into equation 1, then predictive travel time shown below can be used:

$$T = tf\left\{1 + 0.2\left(\frac{v}{Q}\right)^{10}\right\} \quad (2)$$

Capacity in Eq. (2) can be estimated by various methods such as mathematical or simulation equations. It has been shown by Ben-Edigbe and Ferguson (2005) that empirical studies are best estimated by fundamental diagram method where flow, speed and density drive traffic operation. The linear equation is based on flow, speed and density relationship where:

$$q = uk \quad (3)$$

where,
q: Denotes flow
u: Denotes speed
k: Denotes density

Greenshields (1935), derived speed and density linear relationship shown below:

$$u = u_f - \frac{u_f}{k_j}k \quad (4)$$

As contained in many literatures, flow/density curve has two sections (constrained and unconstrained). The constraint is capacity. The two sections behave differently. Flow oscillates in the unconstrained section and flow rate contracts in the constrained section. According to Minderhoud *et al*. (1997) where the flow/density relationship has been used to compute capacity the critical density is reached at the apex point. Flow/density model Eq. (4) is a fusion of Eq. (3) and (5)

$$q = k\left(u_f - \frac{u_f}{k_j}k\right) \quad (5)$$

For maximum flow:

$$\frac{\partial q}{\partial k} = u_f - 2\left(\frac{u_f}{k_j}\right)k = 0$$

Critical density:

$$k_c = \frac{u_f}{2\left(\frac{u_f}{k_j}\right)}$$

Now, if k_c is then plugged into Eq. (5), capacity (Q) can be estimated:

$$Q = (u_f)\frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_j}\left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \quad (6)$$

where,
u_f : The free-flow speed

k_j : The jam density

Note that free-flow travel time (t_f) in Eq. (1) is a function of road length (L) and free-flow speed (u_f). It can be written as:

$$t_f = \frac{L}{u_f} \tag{7}$$

After the free-flow section, vehicles enter the transition zone with reduced speed (u_z) so that the travel time is adjusted to transition travel time (t_t) and computed as:

$$t_\tau = \frac{2L}{v_f + v_z} \tag{8}$$

Delay is defined as an extra time spent by drivers against their expectation then the delay (d_d) due to deceleration (from $u_f$to u_z) is:

$$d_d = t_\tau - t_f = \frac{2L}{v_f + v_z} - \frac{L}{v_f} \tag{9}$$

This delay is called deceleration delay because it occurs when vehicles decelerate before entering the median opening zone. Delay when vehicles travel through the median opening zone is the difference between the travel times needed to pass the median opening zone at the reduced speed and the travel time to pass the same length of the roadway without median opening zone at free-flow speed. If the length of a median opening zone is Lm, then the delay (d_z) of a vehicle travelling within the median opening zone can be calculated as:

$$d_z = L\left(\frac{1}{v_z} - \frac{1}{v_f}\right) \tag{10}$$

This delay in Eq. (10) is incurred from reduced speed through the median opening zone. Upon exiting the median opening zone at reduced speed vehicles accelerate to free-flow speed. Time needed to reach the free-flow is a delay tied to loss time. Where average acceleration (a) the distance (S) travelled due to speed change from u_z *to*$u_f$is:

$$s = \frac{v^2 f - v^2 z}{2_a} \tag{11}$$

Time needed for a vehicle to accelerate from *uz* to*uf*is:

$$t_1 = \frac{v_f - v_z}{a} \tag{12}$$

Assuming no midblock median opening facilities, time needed for a vehicle to travel the same distance is:

$$t_2 = \frac{s}{v_f} = \frac{v^2 f - v^2 z}{2_a v_f} \tag{13}$$

Therefore, the delay for a vehicle to accelerate to free-flow speed is the difference between time t_1 and t_2:

$$d_a = t_1 - t_2 = \frac{v_f - v_z}{a} - \frac{v^2 f - v^2 z}{2_a v_f} \tag{14}$$

The average waiting time that an arrival vehicle spends before entering the midblock median opening zone is:

$$d_w = \frac{q_\lambda}{Q(Q - q_\lambda)} \tag{15}$$

where,

Q : Average departure rate from the queue
$q\lambda$: Traffic flow arrival rate

Total travel time delay is:

$$d_T = V_h(d_d + d_z + d_a + d_w) \tag{16}$$

where,

v_h : Hourly flow of arrival vehicles at hour *i*

Given the midblock median U-turn opening facilities scenario described so far in the paper, it is necessary to know the distribution of vehicle arrivals into the distressed zone. Sometimes vehicle queue can occur during free-flow period because vehicle arrival is ransom and probabilistic. Nonetheless queuing is a delay function that can be analysed with the application of queuing theory. Where the distressed zone is assumed to be a server with entry and exit points for vehicles in order of arrival, the average arrival rate of the vehicles is the traffic flowrate and the service rate of the system is the capacity of the distressed zone. Because of the randomness of road traffic, the queuing system can be represented as a system with Poisson arrivals, exponentially distributed service times and one server. Basically queuing theory assumes that vehicle arrivals are independent, motorists do not leave or change queues, large queues do not discourage motorists and the mathematics of waiting lanes has exponential distributions,Ngoduy(2011). Frankly these assumptions are slightly exaggerated; nevertheless, they provide reasonable answers. The queuing systems are usually described by three values: arrival distribution, service distribution and number of servers. M/M/1 where the rate of arrival is exponentially distributed, hump service times are exponentially distributed and there is only one hump,Li*et al*. (2011). Note that M denotes Markovian or exponentially distributed. Now if motorists are arriving at exponentially distributed rate λ, then the probability that there will be *k* driver after time *t* is:

$$P_k(t) = \frac{(\lambda t)^k}{k!} e^{-\lambda t} \tag{17}$$

Where utilization = ρ = λs = faction of time the hump is busy.

Based on Erlang's queuing theory the expected number of vehicles in the queue is:

$$E_{(n)} = \sum_{n=0}^{\infty} nP(n) = \frac{q_\lambda}{Q-\lambda} \quad (18)$$

The average waiting time that an arrival vehicle spends before entering the asphalt pavement distress area is:

$$d_w = E_{(m)} = \frac{q_\lambda}{Q(Q-q_\lambda)} \quad (19)$$

where,

Q : Average departure rate from the queue

$q\lambda$: Traffic flow arrival rate

Because there is a probability that the queue will be zero, the average queue length will not be one less than the average number in the queue. The average queue length (or the average number of vehicles in the waiting line) is:

$$E_{(m)} = \sum_{n=1}^{\infty}(n-1)P(n) = E(n) - q_\lambda/Q = \frac{q_\lambda^2}{Q(Q-q_\lambda)} \quad (20)$$

where,

E (w) : Average time a vehicle spends queuing

E (m) : Average queue length

E (n) : Expected number of queue

Q :Average departure rate from the queue

$q\lambda$: Traffic flow arrival rate

Delays at exit midblock carriageway lane can trigger erratic driver reaction especially in circumstances where the critical gap on the major road is smaller than reaction time.

Safe road crossing is a complex perceptual-motor task that requires accurate perception of the gap sizes in a dynamic stream of traffic and fine coordination tosynchronize the onset of movement with the approaching gap. Gap is very similar to headway minus the vehicle length. It is a measure of the time that elapses between the departure of the first vehicle and the arrival of the second at the designated test point. Gap acceptance plays a crucial role in safe driving. At the exit carriageway lane of midblock facilities, cautious drivers are more likely to reject small gaps than erratic drivers who may misjudge critical gap. Critical gap is usually considered as a fixed value or to follow a certain distribution. It is the threshold by which drivers judge whether to accept a gap or retain holding position. If the critical gap is larger than reaction time, drivers are more likely to enter the traffic stream on the major road. However, where gaps are well below reaction time, it can be assumed that the probability of accident occurring would be profound.

The passenger car equivalent values being an instrument of highway traffic flow computation must also be modified to take into account weaving, diverging and merging. Ignoring PCE modifications could lead to grossly inaccurate traffic estimates. Since PCE measures the impact that a mode of transport has on traffic variables compared to a passenger car underprevailing conditions, it follows that changes in prevailing conditions will have relative effect on pce values. In essence pce values are dynamic. Therefore traffic flow model equations must be modified accordingly. The term 'passenger car equivalent' was defined in Highway Capacity Manual (HCM) (2010) as 'the number of passenger cars displaced in the traffic flow by truck or a bus under the prevailing roadway and traffic conditions'. This definition still holds today and the use of such equivalents is central to road capacity analysis where mixed traffic stream are present. The headway evaluation criteria could be applied to many traffic situations such as at intersection and basic highway segments or mid-block sections. Whereas headway data can be obtained in the field with relative ease, other evaluation criteria such as delay, density and speed are expensive as such methods based on these adopt the simulation approach. According to Seguin *et al*. (1998) and Ben-Edigbe and Ferguson (2005) notwithstanding, the method adopted, modified

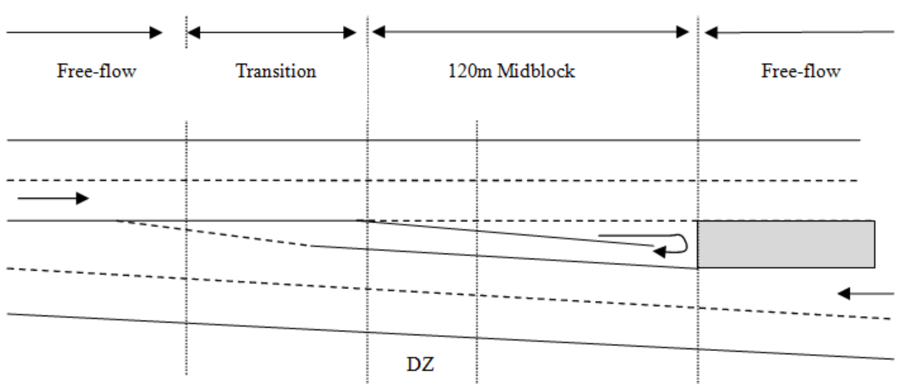

Fig. 1: Typical layout of survey sites

passenger car equivalent values will have no effect on the outcome of the study. Therefore, a simplified passenger car equivalency headway method was used. There is no need to build a new one. The passenger car equivalency method used in this paper is the headway method. The method was first proposed by and involves the following equation:

$$pce_i = \frac{H_i}{H_c} \tag{21}$$

where,

pce_i = Passenger car unit of vehicle class i
H_i = The average headway of vehicle class i
H_c = The average headway of passenger car

Based on the hypothesis that u-turning median opening facilities have significant impact on travel time delay; impact studies were carried out at 2 locations, Malaysia during daylight and dry weather conditions. The setup of median opening U-turn impact study is illustrated below in Fig. 1. The survey data were supplemented with highway design information culled from the Malaysian Public Works Departments Design Manual IDRA Road LayoutDesign (2011). The roadway was divided as shown in Fig. 1 in both directions. Note that ATC denotes automatic traffic counter, FZ denotes, free flow zone, TZ is transition zone, DZis dilemma zone as well as the taper length and MZ is median opening zone with parallel entry/exit lane. Motorists at upstream section are assumed to be driving at free flow speed.

RESULTS AND DISCUSSION

There are three issues to be resolved in this section; travel time delay at the diverging section of the median opening zone, travel time delay at the merging section of the median opening and travel time delay at the u-turn exit end of the median opening. At the transition and dilemma zones, outer lane speeds were generally higher than the inner lane speeds because weaving intensity was more pronounced at the inner lane as motorists maneuver for median opening entry position.

From Table 1, it can be seen that speed drop which is the key parameter is more prominent at the diverging than the merging section. It was observed that at themerging section,U-turntrafficflows are dependent on traffic flow on the major road. If the average gap in the major road adjacent to the exit laneisconsiderably small, then it can be postulated that drivers' exposure to collision is heightened as they become impatient for acceptable gap to occur. Should the gap time be violated or misjudged, the lead vehicle on the major roadway may break abruptly, sometimes violently. It's up to the drivers at the exit lane to get the timingright.As shown in Table 2, loss time, queue and travel time delays are present at the diverging section of the median opening zone at all sites suggesting that midblock facilities can be partially responsible. Average waiting time that an arrival vehicle spends before entering the median opening zone account for longest travel time delay and this may be connected to weaving intensity and jostling for prime median opening zone position. Drivers emerging from the U-turn median lane must wait to gaps to emerge before joining the major road. As shown in Table 3, there is no delay to traffic flow at the merging section of median opening zone because of the absence of speed reduction and mildness of trafficperturbations.

In sum, merging is more difficult than diverging because through traffic flows are traversing along the faster lane. It is often a very dangerous maneuver that can trigger road accident. This is so because drivers along the overtaking lane are forced to either abandon the overtaking move in other to avoid collusion or ignore the risk altogether. In any case critical gapwhich isathresholdbywhichmergingstreamdriversjudge whether to accept a gap or abandon it is an important variable. If the gap is larger than the critical gap, driversaccept it and enter the through traffic; otherwise drivers reject the gap and wait for the next gap.

Table 1: Summary of traffic flow parameters

Site		u_fm/s	u_zm/s	qveh/h	qveh/s	Qveh/s	Hwys	Gaps
Divergingsection	1	21.1	10.8	1530	0.425	0.308	2.35	2.29
	2	30.6	13.1	1366	0.379	0.316	2.64	2.53
Mergingsection	1	25.2	28.5	1468	0.408	0.410	2.45	2.40
	2	22.2	23.1	1552	0.431	0.430	2.32	2.26

Hwy: headway; q: flow; v speed

Table 2: Summary of travel time delays and queues at diverging section

Site	d_d	d_z	d_a	d_w	d_t	E_m	T_f	T_z
1	1.57	4.52	0.74	12.18	5.54	2.75	4.8	9.3
2	1.28	4.36	1.48	18.79	7.73	4.93	3.3	7.7

T_f : Free-flow time, T_z: time (s) at midblock section

Table 3: Summary of travel time delays and queues at merging section

Site	d_d	d_z	d_a	d_w	d_t	E_m	T_f	T_z
1	0.20	0.40	0.05	0.00	0.65	0.00	3.9	3.3
2	0.09	0.17	0.01	0.00	0.92	0.00	4.5	4.4

T_f : Free-flow time, T_z: time (s) at midblock section

Since this is not a priority-controlled intersection the rule of critical gap fixed values or distribution does not strictly apply. It's up to drivers to get the merge-timing right. Delays at midblock U-turn lane are moderate and somewhat acceptable; however, when a driver arrives at the exit lane and misjudge a gap in the major road traffic stream, the consequences could befatal.

CONCLUSION

It is recognized that traffic flow perturbations contribute to travel time delay at the median opening zone. Even though travel time delay was not recorded for traffic flow on the major road at the merging section, there is risk inherent vehicle merging at this section. This so because acceleration and merging is a deft maneuver, vehicles attempting to enter the stream can only do so during larger gaps of successive vehicles in the fast lane. The paper concluded that:

- Delay at the diverging section would result from median opening
- Extent of delay is dependent on traffic volume
- Traffic flow rate contractions precede travel time delay
- Exitlaneof the median opening zone is not a significant contributor to delay.

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