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Effect of U-turning Maneuvers at Midblock Facilities on Traffic Kinematic Waves

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Abstract: Direct Midblock U-turn facilities are built on dual carriageway road in Malaysia mainly to reduce the number of conflicts at intersections without consideration for their effect on traffic kinematics. Direct midblock U-turn facilities encourage vehicle deceleration when diverging to and acceleration when merging from the U-turn lane. Surely these deft maneuvers have traffic kinematic consequences. The study is aimed at determining the extent of traffic kinematic waves induced by u-turning maneuvers at roadway midblock facilities. The objectives were to estimate and compare volume and density per directional flow before and at midblock facilities. Impact studies were carried out at two sites in Malaysia during daylight and dry weather conditions. Traffic volume, speed, headway and vehicle types' were collected continuously for eight weeks for both directional traffic flows. About 150,000 vehicles were surveyed. Survey data were supplemented with information culled from the Malaysian Public Works Departments highway design manual. Results show that kinematic waves from deceleration and diverging to entry lane are less severe than those caused by acceleration and merging from exit lane to major carriageway. There is no evidence to suggest that midblock u-turning facilities can be called to account for severe kinematic waves on approach to the entry lane. However, significant kinematic waves of about 21 km h^{-1} occurred only when merging and. The study concluded that traffic kinematic wave is more heightened in the vicinity of the Midblock exit lane than entry lane; and also that shockwaves may be triggered by vehicles attempting to enter the major road traffic stream.

Key words: U-turn, midblock, traffic shockwave, kinematics, merging, diverging

INTRODUCTION

Midblock U-turn facilities are often constructed as a cost effective way of alleviating congestion and road safety problems. Some, highway midblock U-turn facilities are built to complement existing road geometric 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. That may be so, but there are road safety consequences that are often ignored. On approach to Midblock u-turning facilities, drivers alone must decide when it is safe to merge, diverge and accept emerging gaps. Misjudgement of ensuing gaps is not an option. When exiting the facility, driver may reject gap on the major road and wait for a subsequent gap. Poor gap acceptance decisions have severe consequences. They may cause traffic shockwave and lead to accidents. Weaving, merging and diverging are deft traffic stream manoeuvres that are often laden with profound risk of accident occurring. In Malaysia where the left hand driving rule is in place, drivers will tend to keep to the right lane; decelerate when diverging, accelerate when converging. These manoeuvres are deft and dangerous. Arguments have been advanced by some opponents of infrastructure modification projects that the increased numbers of U-turn facilities may compromise safety and exacerbate operational problems affected roadway. In any case, the existence of traffic shockwave at the weaving area of midblock u-turning facilities is a clear indication of inherent road safety risk. So, it can be postulated that interactions between traffic streams on approach to midblock U-turn facilities have adverse effect on driver reactions and the absence of significant kinematic shockwaves also suggests that safety is not necessarily an issue. In any case, the study is aimed at estimating the extent of traffic kinematic waves caused by right u-turning movements at direct midblock facilities. The objectives were to estimate and compare volume and density per directional flow before and at direct midblock U-turn facilities.

LITERATURE REVIEW

Malaysia is made up of thirteen states. It has a land area of 329,847 m^2 and the capital city is Kuala Lumpur.

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Highways in Malaysia are classified by the ministry of works as expressway, federal, state, municipal highways and others. Federal Highways which is of interest to this study is the busiest highway. They are often built with 2 carriage way lanes in each direction with an operating speed limit of 90 km h^{-1}. It is conventional wisdom that motorists are expected to travel faster when overtaking on right lane as shown below in Fig. 1. Over the past few decades, the use of U-turn as an alternative to direct right turn for the left-hand traffic is profound in Malaysia. Past studies have indicated that direct right turn manoeuvres increase delay, conflicts and crashes and they reduce capacity. Presently, there is a lack of information especially on the extant of traffic shockwave propagation induced by midblock U-turn facilities.

As contained many literatures (TRB, 1997), midblock u-turning facilities are effective conflict-points reduction mechanism at intersections. An intersection without treatment has 32 conflict points (16 crossing, 8 diverge, 8 merge), however, at treated intersection conflict points are reduced to 8 (1 crossing, 3 diverge, 4 merge). The more common right turn treatments are: flash median with one way right turn lane, raised curb median with alternating right turn bays, flush median with alternating right turn and undivided cross section as contained in National Cooperative Highway Research Program-NCHRP report 395 (TRB 1997). As contained in Malaysia's Iskandar Development Regional Authority Area Character Statement-Blueprint for Iskandar Malaysia (IDRA 2011), one potential treatment to combat congestion and safety problems at intersections is the installation of non-traversable medians and directional median opening has produced an increased number of U-turns on multilane divided roadways. In any case all traffic flow models and theories must satisfy the law of conservation of the number of vehicles on the road according to Tanner (1962). Assuming that the vehicles are flowing from upstream to downstream, the continuity equation can be written as:

$$\frac{ak(x,t)}{at}+\frac{aq(x,t)}{ax}=0 \qquad (1)$$

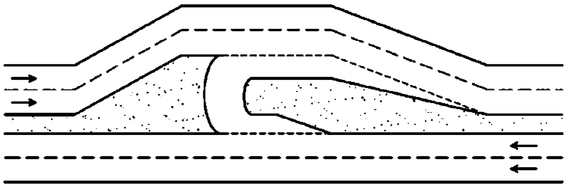


Fig. 1: Recommended layout for direct U-turn

where, x denotes the spatial coordinate in the direction of traffic flow, t is the time, k is the density and q denotes the flow. However, one cannot get two unknowns, namely k (*x*; t) by and q (*x*; t) by solving one equation. One possible solution is to write two equations from two regimes of the flow, say before and after a bottleneck so that flow before and after will be same, or if you like:

$$k_1 v_1 = k_2 v_2 \qquad (2)$$

From this the shockwave velocity can be derived as:

$$v_w = \frac{q_2 - q_1}{k_2 - k_1} \qquad (3)$$

Where:

v_w = Propagation velocity of shock wave (km h^{-1})
q_2 = Flow before (veh h^{-1})
q_1 = flow after conditions (veh h^{-1})
k_2 = Density before (veh km^{-1})
k_1 = density after (veh km^{-1})

Traffic Kinematic waves: Traffic kinematic waves are by-products of traffic congestion. They are transition zones between two contrasting traffic states (free-flow and congestion). Merging and acceleration is a deft manoeuvre because through traffic flows have priority in the conflict sections and vehicles attempting to enter the stream can only do so during larger gaps of successive vehicles in the fast lane. Merging is more difficult than diverging because through traffic flows are traversing along the faster lane. It is often a very dangerous manoeuvre 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 gap which is a threshold by which merging stream drivers judge whether to accept a gap or abandon it is an important variable. If the gap is larger than the critical gap, drivers accept it and enter the through traffic; otherwise drivers reject the gap and wait for the next gap. It's up to drivers to get the merge-timing right. Traffic kinematic waves are one of the major safety concerns because the sudden change of conditions drivers experience as they pass through a shockwave often can cause accidents. If the assertion that, 'traffic kinematic waves are by-products of traffic congestion' is to hold, then the 'traffic flow after conditions and density after' denoted in equation 3 as q_1 and k_1 must be congested flowrate and density, respectively. Therefore, a threshold capacity (Q) must be estimated in other to ascertain whether the threshold line has indeed been crossed as shown below in Fig. 2. Where the threshold capacity has been crossed

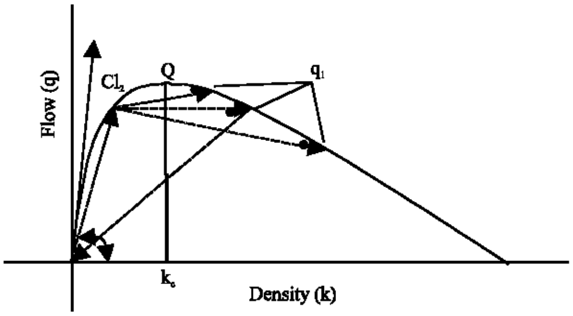


Fig. 2: Hypothetical traffic khockwave along 3 lines (q_1)

the passenger car equivalent values being an instrument of capacity computation must also be modified. 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 passenger car equivalent (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 under prevailing 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, 2001) 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. The passenger car equivalency method used in this study is the headway method. The method was first proposed by and involves the following equation:

$$PCE_i = \frac{H_i}{H_c} \tag{4}$$

where, PCE_i is the passenger car unit of vehicle class I. H_i is the average headway of vehicle class i and H_c is the average headway of passenger car.

When computing capacity, Greenshields *et al.* (1935), derived speed and density linear relationship shown below:

$$v = v_f - \frac{v_f}{k_j} k \tag{5}$$

Given that Speed (v) is a function of density (k) and flow (q):

$$v = \frac{q}{k} \Rightarrow q = vk \tag{6}$$

If equation 6 in plugged into 5, then:

$$q = k\left(uf - \frac{uf}{k_j} k\right) \tag{7}$$

where, v_f is the free-flow speed and k_j is the jam density.

According to Ben-Edigbe (2010), where the flow/density relationship has been used to compute roadway capacity the critical density is reached at the apex point. Up till that point, traffic stream is operating under unconstrained conditions not free flow as often wrongly mentioned in many literatures. Beyond the apex point, traffic flowrate is operating under constrained condition. Since the study is interested in estimating the capacity change due to midblock u-turning movement, the choice of precise value of critical density need not be very critical to the outcome of this study. Consider equation 7 again, for maximum flow:

$$\frac{\partial_q}{\partial_k} = uf - 2\left(\frac{uf}{k_j}\right)k = 0 \tag{8}$$

Then, critical density:

$$k_c = \frac{uf}{2\left(\frac{uf}{k_j}\right)} \tag{9}$$

If k_c is plugged into equation 6 highway capacity (Q) can be estimated:

$$q = (uf)\frac{uf}{2\left(\frac{uf}{k_j}\right)} - \frac{u_f}{k_j}\left(\frac{uf}{2\left(\frac{uf}{k_j}\right)}\right)^2 \tag{10}$$

If Eq. 10 is plugged into Eq. 3 then, traffic shockwave velocity can be re-written as:

$$v_w = \frac{q_2 - \left\{ (uf)\frac{uf}{2\left(\frac{uf}{k_j}\right)} - \frac{u_f}{k_j}\left(\frac{uf}{2\left(\frac{uf}{k_j}\right)}\right)^2 \right\}}{k_2 \left\{ \frac{u_f}{2\left(\frac{uf}{k_j}\right)} \right\}} \qquad (11)$$

According to Ben-Edigbe and Ferguson (2005) where the flow/density relationship has been used to compute roadway capacity where critical density is reached at the apex point. Up till that point, traffic stream is operating under unconstrained conditions not free flow as often wrongly mentioned in many literatures. Beyond the apex point, traffic flowrate is operating under constrained condition. Since the interest is in estimating the traffic kinematic changes due to midblock right u-turning movement, the choice of precise value of critical density need not be very critical to the outcome of this study.

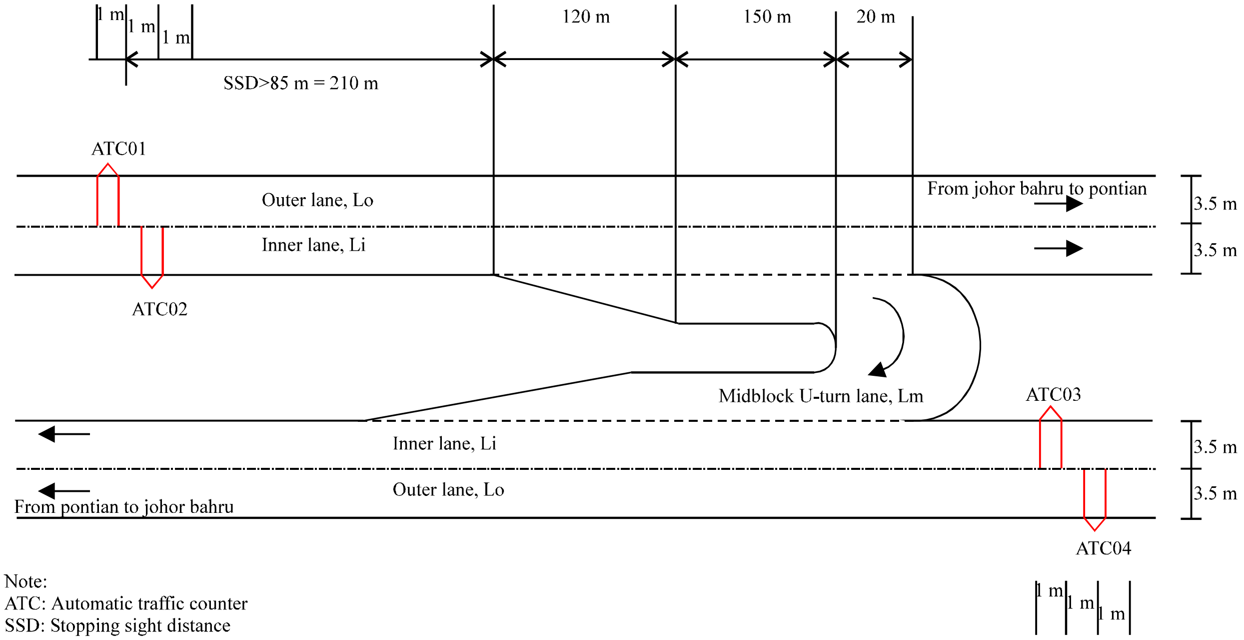
SETUP OF IMPACT STUDY AND DATA COLLECTION

The setup of midblock u-turning impact study is illustrated below in Fig. 3. The dual carriageway roads at Senai and Kulai have been selected for the study after careful considerations and coded as site 1 and site 2, respectively. The survey data were supplemented with highway design information culled from the Malaysian Public Works Departments manual. The roadway was divided into three sections (upstream, transition and downstream) in both directions. The upstream section was set at a distance greater than Stopping Sight Distance (SSD) so as to minimise the influence of midblock facilities on the carriageway lanes. Motorists at upstream section are assumed to be driving at free flow speed. Motorists at the downstream are traversing the right midblock U-turn lane by way of deceleration on entry and acceleration on exit:

$$\text{SSD}(m) = \left\{ (0.278\,vt) + (0.039\frac{v^2}{a}) \right\} \qquad (12)$$

where, t is perception time (assume 2.5 sec), v is approach speed and a is deceleration time, with rate taken as 3.4 m s^{-2}.

Traffic volume, speeds, vehicle types, headways and gaps were recorded continuously for 8 weeks both directions under dry weather and daylight conditions. Over 500,000 vehicles per roadway direction were captured on the data logger. Note that for the ease of referencing, lane 1a and 1b are influenced by diverging; whereas lanes 2a and 2b are influenced by merging; Note also that, SSD = driver perception/reaction distance (d_1)+braking distance (d_2).



Note:
ATC: Automatic traffic counter
SSD: Stopping sight distance

Fig. 3: Typical layout of survey site

EMPIRICAL RESULTS AND FINDINGS

Traffic volume, speed, vehicle types collected at two strategic sites in Malaysia were analysed in order to determine the extent of traffic kinematic wave induced at midblock U-turn facilities. A case for dynamic passenger car equivalent values was made on the premise that, ignoring their modifications could lead to grossly inaccurate estimates with significant consequences for study outcomes. Empirical findings are presented and discussed below using a step wise procedure:

Step1: Traffic volumes were converted into flows using appropriate passenger car units. Aggregated traffic data were disseminated and fitted into peak and off peak period under day light and dry weather conditions

Step 2: Determine the threshold capacity function under free-flow conditions and test model equations for validity. Peak data were used to determine the boundary between flow-flow (ff) and congestion sections of the flow-density curve as shown below in Fig. 4 in the case of site 1

Step 3: Determine off-peak model coefficients and test for validity as shown below in Table 1. In Table 1, the coefficient of determination (R^2) is greater than 0.5 suggesting that the equation is useful for modeling. Assuming that an average road space per vehicle is 5 m and given that the length of standard exit lane 150 m, it can postulated that the maximum number of vehicle at exit and entry midblock lanes is 30 vehicles each. As shown in Table 1 above, at site 1, diverging free-flow speed is 66 km h^{-1} and the jam density is 157 veh km^{-1} (24 veh/150 m<30 veh/150 m), whereas the merging speed is about 72 km h^{-1} and the corresponding jam density is 131 veh km^{-1} (20 veh/150 m<30 veh/150 m). At site 2, the diverging free-flow speed is 86 km h^{-1} and the jam density is 72 veh km^{-1} (11 veh/150 m<30 veh/150 m), whereas the merging speed is about 56 km h^{-1} with a corresponding 77 veh km^{-1} (12 veh/150 m<30 veh/150 m), jam density. So, it can be suggested that traffic congestion at the exit and entry lanes is neither present nor responsible for kinematic waves at sites 1 and 2

Step 4: Determine off-peak traffic flow rates and check that the congested flowrate is beyond the estimated capacity in step 2. For example; at site 1, congested flowrate 1550 pcu h^{-1} and the corresponding density 36 veh/km>peak flow rate 2163 pcu h^{-1} and peak density of 23 veh km^{-1}

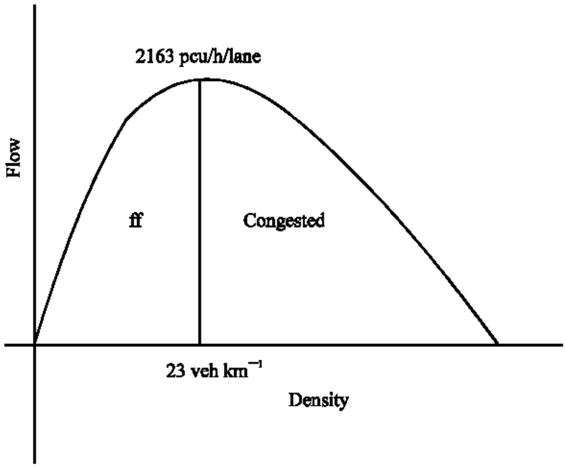


Fig. 4: Typical road segment threshold capacity at peak

Table 1: Estimated model coefficients

Manoeuvre	Site	Model equation	R^2
Diverge	1	$U = -0.4203\,k+66.17$	0.9833
		$q = 66.17\,k-0.4203\,k^2$	0.9833
	2	$U = -1.203\,k-86.37$	0.9266
		$q = 86.37\,k-1.203\,k^2$	0.9266
Merge	1	$U = -0.5485\,k+71.847$	0.9449
		$q = 71.847\,k-0.5485\,k^2$	0.9449
	2	$U = -0.72\,k+55.73$	0.9063
		$q = 55.73\,k-0.72\,k^2$	0.9063

Step 5: Determine traffic kinematic waves using Eq. 11 as shown below in Table 2. As shown in Table 2 above, computed capacities (Q_2) are less than the threshold capacities (Q) and also that the computed densities (k_2) are greater than the free-flow densities (k_1) at all sites. At sites 1 and 2, estimated kinematic waves of 2 km h^{-1} are within speed variance hence inconsequential whereas acceleration and merging at both sites trigger kinematic waves in excess of 20 km h^{-1}. Therefore, it can be affirmed that drivers' behaviour in the vicinity of midblock facilities are influenced by weaving, sight distance and drivers judgement. Also that deceleration and diverging has insignificant effect on traffic kinematic waves

Step 6: Compare traffic kinematic waves from diverging lane to that of merging lanes for the two sites under observation. As summarised in Table 2, predicted traffic shockwave of about 20 km h^{-1} occurred when converging and 2 km h^{-1} when diverging at the midblock u-turning facilities. Traffic shockwaves of about 20 km h^{-1} at the exit carriageway lane were positive, suggesting that they were when travelling in same direction as traffic stream. Although vehicles may have

Table 2: Traffic flow shockwave using modified PCE

Drivers'behaviour	Site	q_1 pcu/h/ln	k_1 veh km^{-1}	Q pcu h^{-1}	Q_2 pcu/h/ln	k_2 veh km^{-1}	q_1-Q_2	k_1-k_2	vw km h^{-1}
Deceleration and diverging	1	933	33	2509	1043	86	-110	-53	2
	2	1578	23	2163	1550	36	28	-13	-2
Acceleration and merging	1	801	21	2353	1684	66	-883	-45	20
	2	1323	32	2344	1077	39	246	-7	-35

Source: Survey data, Note: v_w-shockwave

difficulty in overtaking and weaving because of deceleration effect, kinematics of traffic flow suggest that weaving of vehicles at decision zone area has not led to shockwave. This is partly because drivers following the lead vehicle are able to appraise traffic stream and control mechanism positively. This has not been the case at the exit lane

DISCUSSION

Previous studies have been concerned with traffic safety at midblock U-turn facilities by comparing accidents records before and after the installation of midblock facilities. Some other studies focus on speed reductions caused by midblock U-turn facilities, often without modifying the passenger car equivalent values. It is also clear from previous studies that some speed reductions would occur in the vicinity of midblock U-turn facilities mainly due to weaving intensity. There is no previous study on traffic kinematic waves caused by direct midblock U-turn facilities. Nevertheless, this study has also shown that speed reduction would result from u-turning movements at direct midblock facilities. Whereas in previous studies, speed reductions were generalized; in this study speed reduction has been shown to be lower and somewhat gradual when motorists are manoeuvring to enter the midblock facilities and higher when they are merging on exit from the midblock facilities. This is a significant finding as it underpins the issue of traffic safety at direct midblock U-turn facilities.

In sum, the presence of significant traffic shockwave on the major traffic stream lends credence to the hypothesis that midblock u-turning facilities have inherent safety problem. If the gap is larger than the critical gap, drivers accept it and enter the through traffic; otherwise drivers reject the gap and wait for the next gap. It's up to the drivers at the exit lane to get the timing right. Merging is more difficult than diverging because the through traffic flows are traversing along the faster lane. It is often a very dangerous manoeuvre 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 essence a driver experiences kinematic wave whenever he/she adjusts his/her speeds in accordance with the behaviour of the car or cars in front, on observing a brake light, or an opportunity to overtake. While it is recognised that midblock u-turn design must be appropriate to the specific needs of a particular country, it can be argued that the depth of understanding and experience gained from this study is more relevant to traffic control and management decision making in Malaysia than readily transferable traffic calming solutions from other countries. Based on the synthesis of evidence in this study it can be postulated that traffic kinematic wave is heightened in the vicinity of the Midblock exit lane; and also that shockwaves may be triggered by vehicles attempting to enter the major road traffic stream.

CONCLUSION

The study is aimed at determining the extent of traffic kinematic waves associated with direct midblock U-turn facilities. The midblock impact studies gave an insight into some of the problems associated with midblock u-turning facilities in Malaysia. Based on the synthesis of empirical evidences obtained from sample survey at sites in Kulai and Skudai in Malaysia, the study concluded that:

- Traffic flowrate contractions will always precede kinematic waves and speed reduction is the main contributor
- There is correlation between traffic safety and kinematic waves
- There is no evidence in the study to suggest that the presence of kinematic waves at the entry lanes is significant. However, significant positive kinematic waves were found at the exit lanes
- The hypothesis that u-turning movement at midblock may induce shockwave at the exit lane is valid

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