Research Article
Effect of U-turning at Midblock Facilities on Weaving Intensity

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Abstract: The study is aimed at determining the extent of weaving intensity induced by u-turning movements at roadway midblock facilities. The objectives are to estimate, weaving and volume ratios, as well as weaving intensity per directional flow. Weaving impact studies were carried out at 4 sites in Malaysia during daylight and dry weather conditions. Twenty four hours traffic volume, speed, headway and vehicle types' were collected continuously for 8 weeks from January to March 2012 for both directional traffic flows. Survey data were supplemented with information culled from the Malaysian Public Works Departments highway design manual. Results show that weaving, deceleration and diverging to entry lane are less severe than those caused by acceleration and merging from exit. The study concluded that weaving intensity is heightened in the vicinity of the Midblock entry carriageway lane.

Keywords: Diverging, merging, midblocku-turn, ramp, weaving

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. Weaving occurs when vehicles crisscross the carriageway lanes often with a view to repositioning for traffic stream advantage. It is inherent because of drivers desire to position their vehicle along the appropriate carriageway lane. Misjudgment 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. 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.

Weaving is often triggered on approach to highway ramps, intersections as well as midblock facilities among others. Some, midblock u-turning 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. Although it can be argued that the presence of traffic shockwave cannot be associated solely with midblock u-turning facilities given that traffic shockwave can occur without their presence. That may be true, but the presence of midblock u-turning facilities may increase the probability of shockwave occurring. A U-turn refers to vehicles performing a 180° rotation to reverse the direction of travel. Often u-turning movements at roadway segments are channelized and aided with splitting islands so that drivers can be on their desired trajectories. Nevertheless the movements are often accompanied with weaving, merging and diverging in the vicinity of the midblock u-turning facilities. So, it can be postulated that U-turning movements will inherently interfere with through traffic by encroaching on part or all of the through traffic carriageway lanes.

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 dangerous manoeuvres beg the question; 'what are the induced traffic flow consequences when the lead vehicle decelerates or accelerates abruptly? The study reports on driver reactions to weaving, merging and diverging within the context of transport policy aimed at changing travel behaviour. When ascertaining the extent of drivers' reaction induced by weaving, merging and diverging at midblock u-turning facilities the study focused on key parameters like, weaving intensity, kinematic shockwaves gap acceptance and delays at u-

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turning exit lane. Specifically, the study explores associations between traffic flows and deft manoeuvres u-turning movements at midblock facilities in other to derive safety indicators or early warning signs that will assist practitioners and policy makers in determining the effectiveness of decision-making. In any case, the study is based on the hypothesis that u-turning facilities at roadway segments have significant impact on weaving, merging and diverging manoeuvres.

LITERATURE REVIEW

Malaysia consists of thirteen states and three federal territories and has a total landmass of 329,847 m^2 separated by the South China Sea into two similarly sized regions, Peninsular Malaysia and Malaysian Borneo (DRA, 2011). The capital city is Kuala Lumpur. In 2010 the population exceeded 27.5 million, with over 20 million living on the Peninsula. Malaysian highways are classified by the ministry of works as expressway, federal, state, municipal highways and others. State highways connect district headquarters and are normally single carriageway road. Municipal highways connect residential, commercial and other roads within their district of influence. The expressways are defined as high-speed routes with at least four lanes (2 lanes/carriageway) with full access control, grade-separated interchanges and high design speed limit of 120 km/h, allowing the maximum speed limit of 110 km/h. It has a total length of about 1,850 km. Federal Highways connect all state capitals and city of Kuala Lumpur. It is the busiest highway. They are often built with 2 carriageway lanes in each direction and an operating speed limit of 90 km/h. It is conventional wisdom that motorists are expected to travel faster when overtaking on right lane.

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. 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 used on urban and suburban arterials 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 NCHRP Report 395 (TRB, 1997). 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 (DRA, 2011).
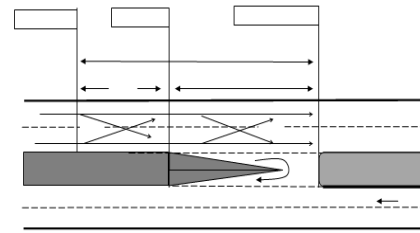

Fig. 1: Typical weaving, merging and diverging diagram

Weaving, diverging and merging literature: Interaction between traffic streams on approach to midblock U-turn facilities has insignificant adverse effect on driver reactions and the absence of significant kinematic shockwaves also suggests that safety is not necessarily an issue here. Capacity and 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 be fatal. Acceleration and merging 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. 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. As shown Fig. 1, four critical geometric variables have significant weaving effect on drivers' reaction and by extension the quality of road service, they are; length of weaving area, width of weaving area, number of lanes in the weaving area and of course lane configuration.

Consider Fig. 1 again and note that; Total flow per direction, $q_A = q_B + q_C$:

AC = Entry flow
BC = Exit flow

In a typical weaving area, weaving and non-weaving flows exist. Now, let q_w be weaving flow and q_0 be non-weaving flow:

Total weaving flow (q_w) can be taken as $q_{w1}+q_{w2}$
Total non-weaving flow (q_0) can be taken as $q_{01}+q_{02}$

If the total flow, $q = q_w + q_0$

Volume ratio $VR = \dfrac{q_w}{q}$ (1)

Weaving ratio, $WR = \dfrac{q_{w2}}{q_w}$ (2)

Since each lane has an impact on the extent of lane changing and their ensuing intensity, the average speed of weaving and non-weaving vehicles can be taken as:

$$v_i = v_{min} + \frac{v_{max}-v_{min}}{1+w} \tag{3}$$

where, v_{min} is the minimum speed in the weaving area; v_{max} is the maximum speed in the weaving area and Speed (v) as shown below in Eq. (4) is a function of density (k) and flow (q):

$$v = {}^{q}/_{k} \Rightarrow q = vk \tag{4}$$

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

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

If Eq. (5) in plugged into 4, then:

$$q = k\left(u_f - \frac{u_f}{k_j}k\right) \tag{6}$$

where,
v_f = The free-flow speed
k_j = The jam density

According to Ben-Edigbe and Ferguson (2009) 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 flow rate is operating under constrained condition. Since our interest is in estimating the traffic kinematic changes due to right u-turning movement at midblock facilities, the choice of precise value of critical density need not be very critical to the outcome of this study. Consider Eq. (6) above, for maximum traffic flow rate:

$$\frac{\partial q}{\partial k} = u_f - 2\left(\frac{u_f}{k_j}\right)k = 0 \tag{7}$$

Then, critical density:

$$k_c = \frac{u_f}{2\left(\frac{u_f}{k_j}\right)} \tag{8}$$

where, k_c is the critical density. If Eq. (5) is plugged into Eq. (5) then, optimum speed can be re-written as:

$$v_0 = \frac{u_f\left(\dfrac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right) - \left(\dfrac{u_f}{k_j}\left(\dfrac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)\right)}{\left\{\dfrac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right\}} \tag{9}$$

Now, let $v = v_i$, v_{min} = optimum speed (v_o) and $v_{max} = v_f$; So that Eq. (3) can be rewritten as:

$$v = v_o + \frac{v_f - v_o}{1+w} \tag{10}$$

Then, weaving intensity is given by:

$$w = 1 - \left(\frac{\left(v_o + \frac{v_f - v_o}{1+w}\right) - v_o}{v_f - v_o}\right) \tag{11}$$

Note that HCM (Highway Capacity Manual) (2000) suggests that weaving intensity can also be estimated where,

$$w = \frac{a(1+VR)^b (q/N)^c}{L} \tag{12}$$

a = 0.15; b = 2.2, c = 0.97; d = 0.8 for weaving speeds and

a = 0.0035; b = 4.0, c = 1.3; d = 0.75 for non-weaving speeds

Modification of passenger car equivalent values: 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 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 HCM (Highway Capacity Manual) (2000) 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
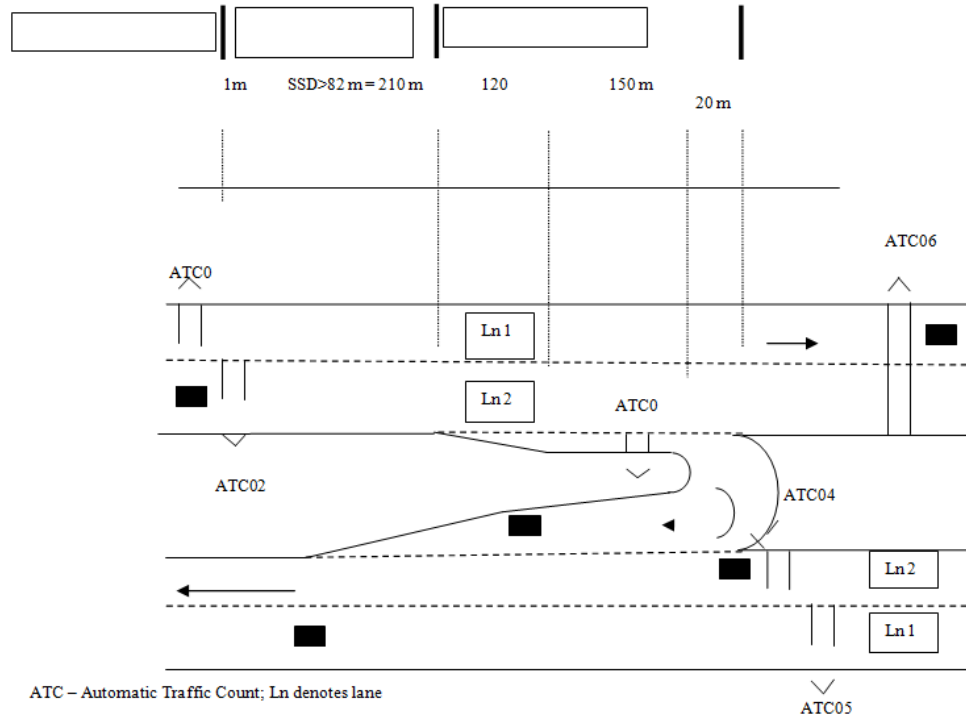
Fig. 2: Typical layout of survey site

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:

$$PCE_i = \frac{H_i}{H_c} \qquad (13)$$

where,
PCE_i = The passenger car unit of vehicle class i
H_i = The average headway of vehicle class i
H_c = The average headway of passenger car

SETUP OF MIDBLOCK IMPACT STUDY

The setup of midblock u-turning impact study is illustrated Fig. 2. The dual carriageway Federal Highway FT001 Senai, Kulai in the Johor State of Malaysia has been selected for the study after careful considerations. The survey data were supplemented with highway design information culled from the Malaysian Public Works Departments manual.

Note also that, SSD = driver perception/reaction distance (d_1) + braking distance (d_2):

$$SSD\ (m) = \left\{ (0.278vt) + \left(0.039\frac{v^2}{a} \right) \right\} \qquad (14)$$

where,
t = Perception time (assume 2.5 sec)
v = Approach speed
a = Deceleration time, with rate taken as 3.4 m/sec^2

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 minimize the influence of weaving and deceleration/acceleration 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. Twenty four hour traffic volume, speeds, vehicle types, headways and gaps were recorded continuously for 8 weeks (January-March 2012) for both directions. Over 500,000 vehicles/roadway direction were captured on the data logger. Study was carried out under dry weather and daylight conditions.

Note that for the ease of referencing, the survey site has been coded as follows.

Site 001: Lane 1a and 1b are influenced by diverging

Site 002: (Lanes 2a and 2b are influenced by merging

RESULTS

Traffic volume, speed, vehicle types collected at four strategic sites in Johor, Malaysia were analysed in

Table 1: Estimated volume ratio and weaving ratio

	q_{o1}	q_{o2}	q_o	q_{w1}	q_{w2}	q_w	q	VR	WR
Site 001	985	801	1875	187	225	412	2287	0.180	0.546
Site 002	933	755	1688	193	339	532	2036	0.262	0.637

Total flow: $q = q_w + q_o$; Volume ratio: $VR = q_w/q$; Weaving Ratio: $WR = q_{w2}/q_w$

Table 2: Estimated flow speed and density

Site	Model equation		R^2	v_f	k_j	v_o	k_o
Site 001	Lane 1a	$U = -0.4203k + 66.17$	0.9833	66.170	157	-	-
		$q = 66.17k - 0.4203k^2$	0.9833	-	-	34	79
	Lane 1b	$U = -0.7289k + 65.48$	0.9266	65.480	90	-	-
		$q = 65.48 - 0.7289k^2$	0.9266	-	-	33	45
Site 002	Lane 2a	$U = -0.5889k + 62.984$	0.9449	62.984	107	-	-
		$q = 62.984k - 0.5889k^2$	0.9449	-	-	32	54
	Lane 2b	$U = -0.5485k + 71.847$	0.9063	71.847	131	-	-
		$q = 71.847k - 0.5485k^2$	0.9063	-	-	36	66

v_f: Free-flow speed; v_o: Optimum speed; k_j: Jam density; k_o: Optimum density

Table 3: Weaving intensity

Site	v	v_o	v_f	Total	w	PD (m)	BD (m)	SSD (m)
001	57.3	34	66.2	0.72	0.28	45.97	47.73	93.7
002	50.5	36	71.8	0.41	0.59	49.86	58.47	108.3

v (km/h); PD: Perception distance; BD: Braking distance; SSD: Sight distance = PD + BD; 66.2 km/r = 18.39 m/sec also 71.8 km/h = 19.94 m/sec

order to identify impacts of midblock U-turn facilities on weaving, merging and diverging on driver reactions. Tanner (1962) derivations were employed to estimate delay. In addition Tanner derivation for maximum discharge for minor road was also relied upon. 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. Weaving and merging interaction between traffic streams on approach to the facility, queues and delays at the facility and also, gaps and merging at exit of the facility were analyzed and presented below using a step wise procedure:

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

Step 2: Determine weaving area and associated parameters; total flow, non-weaving flow, weaving flow, volume ratio and weaving ratio as shown Table 1.

Step 3: Estimate Traffic flow, speed and density as shown in Table 2. Determine the threshold capacity function under free-flow conditions and test model equations for validity. In Table 1, the coefficient of determination (R^2) is greater than 0.5 suggesting that the equation is useful for modeling.

Step 4: Determine weaving intensity using Eq. (11) as shown in Table 3.

Note that:

$$PD = v_f t \text{ and } BD = \frac{(v_f)^2}{2a}$$

where,
PD = Perception distance
BD = Braking distance
v = Speed, t is perception time (2.5 sec)
a = Deceleration time (3.4 m/sec²)

Sight time (sec) for site 001 (deceleration/midblock exit lane) = 93.7/18.39 = 5.09 sec

Sight time (sec) for site 002 (acceleration/midblock exit lane) = 108.3/19.94 = 5.43 sec

If the average gap in the major road adjacent to the exit lane is greater than 5.43 sec, then it can be postulated that drivers can exit safely. However, if the average gap is less than 5.43 sec it can be postulated that drivers' exposure to collision is heightened. So, we need to determine delay, gap and headway along the major roadway adjacent to the exit lane.

Step 5: Determine delay to vehicles exiting midblock U-turn lane; Based on Eq. (14) average delay to vehicles at midblock U-turn exit lane:

$$\overline{w_2} = 8.55 s/veh$$

where,
q_1 = Traffic flow from major road = 0.223 veh/sec
β_1 = Minimum time headway between vehicles on major road = 1.53 sec
β_2 = Minimum time headway between vehicles on minor road = 3.1 sec
α = Average gap in the major merging roadway = 5.51 sec
q_2 = Maximum traffic flow from midblock lane = 0.0875 or 5.25 pce/min or 315 pce/h

Table 4: Traffic flow shockwave using modified PCE

Drivers' behaviour	Lane	q_1 pcu/h/ln	k_1 veh/km	Q pcu/h	Q_2 pcu/h/ln	k_2 veh/km	q_1-Q_2	k_1-k_2	v_w Km/h
Deceleration and diverging	1a	985	21	2604	1471	45	-486	-69	0
	1b	933	33	2509	1043	86	-110	-53	2
Acceleration and merging	2a	801	21	2353	1684	66	-883	-45	20
	2b	755	39	2098	1263	72	-508	-33	15

Survey data; v_w: Shockwave

Q = Capacity; $\rho = q/\mu$; $= 1/8.55 \approx 0.12$

The number of vehicles waiting at the exit point is:

$$E(n) = \left. \frac{\frac{0.0875}{0.12}(1 - \frac{0.0875}{2x0.12})}{} \middle/ (1 - \frac{0.0875}{2x0.12}) \right. = 0.73 \cong 1$$

The average delay to vehicles along dedicated midblock U-turn lane is 8.55 sec/vehicle. As shown Table 3; the sight time for approaching vehicle = 5.43 sec.

The safe gap on the major merging roadway; g = 170/19.94 = 8.52 sec

The average gap in the major merging roadway = 5.51 sec

The number of vehicle waiting at the exit lane to join the through traffic flow is one and the expected delay is 8.55 sec. As illustrated Table 3, the sight time for drivers approaching midblock facilities is 5.43 sec and the average gap on the major merging roadway is 5.51 sec. Based on the configuration of the midblock facilities, the estimated safe gap time is 8.52 sec. The difference between safe gap and average gap is 3.01 which is grated that than the assumed drivers reaction time of 2.5 sec. Therefore for a safe merge, an approaching vehicle travelling at 19.94 m/sec on the major must be at least 170 m away from the exit lane, in order to permit the merging driver a safe passage. Probably that explains why delay per vehicle of 8.55 sec is a high. 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 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 behavior of the car or cars in front, on observing a brake light, or an opportunity to overtake. So, it would be useful to test the exit lane area for traffic shockwave.

Step 6: Test for the presence of traffic shockwave. Shockwaves are one of the major safety concerns because the sudden change of conditions drivers' experience, they can be derived as:

$$v_w = \frac{Q_2 - q_1}{k_2 - k_1} \tag{15}$$

where,
v_w = Propagation velocity of shock wave (km/h)
Q_2 = Flow before (veh/h)
q_1 = Flow after conditions (veh/h)
k_2 = Density before (veh/km)
k_1 = Density after (veh/km)

As summarised in Table 4, predicted traffic shockwave of about 20 km/h occurred when converging and 2 km/h when diverging at the midblock u-turning facilities. Traffic shockwaves of about 20 km/h at the exit carriageway lane were positive, suggesting that they were when travelling in same direction as traffic stream. Although vehicles may have 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.

In any case, 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. Since this is not a priority-controlled intersection the rule of critical gap fixed values or distribution does not apply. Vehicles priority lane can run into conflict sections without giving way and vehicles attempting to enter the stream can only do so during larger gaps of successive vehicles in the fast lane.

CONCLUSION

The weaving, diverging and merging at midblock u-turning impact studies gave an insight into some of the problems associated with midblock u-turning facilities in Malaysia. While it is recognized that midblock u-turning 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 solutions from other countries. Based on the hypothesis that u-turning movement at midblock facilities will heighten weaving intensity and inherent traffic safety, the study concluded that:

- There is correlation between traffic safety and midblock u-turning facilities.
- Weaving intensity on approach to the Midblock u-turning facilities is significant and characterized by speed fluctuation among others.
- There is no evidence in the study to suggest that the presence of traffic shockwave at the entry lane is significant. However, significant positive shockwaves of 20 km/h were found at the exit lane probably due to erratic driving and critical gap misjudgment.
- Estimated delay of about 8.55 sec/vehicle can be expected at exit lane.
- The hypothesis that u-turning movement at midblock will induce shockwave at the exit lane is valid.

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