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Traffic Kinematic Waves at Road Hump Zone: Perceptions and Analysis

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Authors' contributions

This work was carried out in collaboration between all authors. Author JBE designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Author OJ managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Traffic kinematic and shockwaves have often been used interchangeably in any literatures. The paper investigated traffic kinematic waves at road hump zone and their shockwave implications.
Study Design: Road hump impact study.
Place and Duration of Study: The study was carried out at locations along Jalan Universiti, Skudai, Johor Malaysia, between April 2012 and October 2012.
Methodology: Based on the hypothesis that road hump cannot be held solely accountable for traffic shockwave occurrences, with and without road hump impact study was carried out at four sites in Malaysia. Road section was divided into two sections A (without road hump) and B (with road hump). Traffic volume, speed, headway, gaps and vehicle types were collected with automatic traffic counters continuously for eight weeks. Empirical data were supplemented with design data supplied by ministry of works. Data were collated and compared.
Results: Results show that road humps are effective speed reduction mechanism. Although speed reductions were recorded, traffic shockwaves were not recorded and also there was no evidence to suggest that significant kinematic waves were caused at road humps. Differences between traffic shockwave and kinematic wave results affirmed that traffic shockwave will only occur at the capacity constrained section of flow/density curve.
Conclusion: The paper asserted that traffic kinematic wave and shockwave

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propagations are related but not the same and concluded that road humps cannot be held solely accountable for traffic shockwaves. Further, that traffic shockwave is more likely to be caused by the led driver’s erratic behaviour on approach to the barrier.

Keywords: Hump; road; kinematic; rarefaction; shockwave.

1. INTRODUCTION

Road humps are constructed as traffic control mechanism aimed primarily at vehicle speed reduction. They are the most effective speed reduction mechanism currently available and are likely to be in use for some time. Drivers traversing road segments with humps are persuaded to slow down because of induced discomfort to vehicle occupants travelling at overprescribed speed. Three parameters namely; hump heights, spacing and road hierarchy are important when considering road hump as a speed reduction device. Road hump that is of interest to the study was first introduced in 1970s by Transport Research Laboratory England. Initial research comprised of numerous designs; flat top, round top, heights (12mm – 150mm) and lengths (50mm to 3600mm). As to be expected in research there were many failed expectations and dashed hopes. Eventually initial design standards of circular profile hump (3.6m by 100mm height) were installed at trial sites in 1983 and evaluated. The results were conclusive, road humps are effective speed control device. However, the studies focused mainly on speed reduction only. Whilst it is clear that 75mm road humps would reduce speed, their impact on traffic kinematic waves is yet to be fully studied. Also the components of traffic kinematic waves and their unique characteristics have often been ignored in many studies. Traffic kinematic and shock waves have often been used interchangeably in many literatures. Kinematic is the geometry of motion without cause consideration. Since force consideration is not needed, traffic kinematic wave can be construed as a function of density. Traffic shockwave on the other hand is a function of traffic congestion. In essence, traffic stream can experience kinematic wave with shockwave but it cannot experience traffic shockwave without kinematic wave. The paper will address the components of traffic kinematic waves as well asdetermine the type and extent of kinematic wave that may or may not be triggered by 75mm road hump.

2. TRAFFIC KINEMATIC WAVE CONCEPTS / DATA COLLECTION

The paper relied on flow, speed and density fundamental relationship [1], where flow is the dependent variable and density is independent; it is assumed that speed is the resultant slope. Flow, speed and density drive traffic operation. Density drives speed and flow. As contained in many literatures, flow/density curve has two sections (constrained and unconstrained). The constraint is capacity. The two sections behave differently. Speed oscillates in the unconstrained section whereas flow contracts in the constrained section. As contained in main literature, the flow/density curve is made up of two sections (pre and post capacity). Travel speeds oscillate between free-flow and capacity ($0 \leftrightarrow Q$) at the pre-capacity section, oscillation stops at capacity and it is followed by traffic contraction till jam is reached. Where 0.85 is assumed as the bench mark for traffic flow it can be postulated that rarefaction and shockwave will operate between±0.85 of the road capacity. Rarefaction wave may be mild before 0.85 whilst shock wave will be in congestion after 0.85 it can be argued. According to Ben-Edigbe [2,3], the critical density (k_A) is reached at the apex point of the curve shown in Fig. 1. Up till that point, traffic stream is operating under unconstrained conditions not free flow as often mentioned in many literatures. Beyond the apex point, traffic flow is operating under constrained condition.

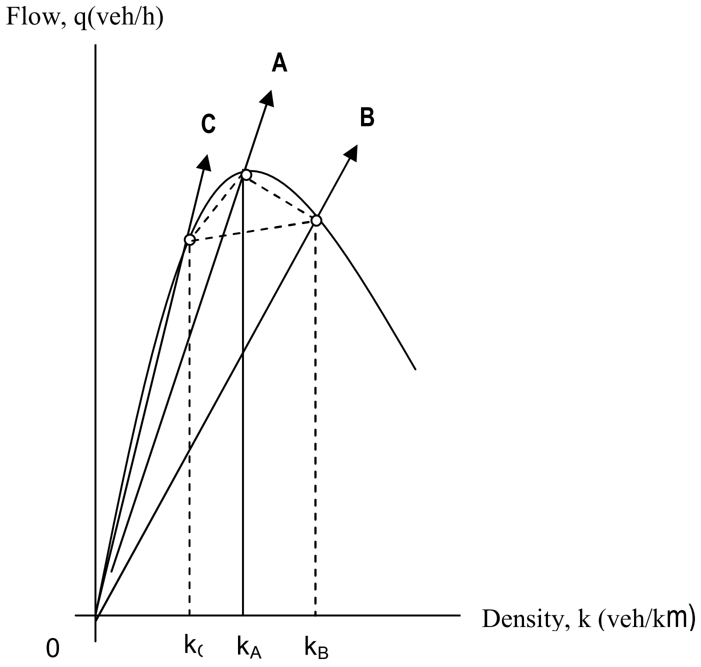

Fig. 1. Flow-density curve with kinematic wave ABC

Traffic shockwave is an abrupt and compressive limited motion that can only happen at the constrained section of the flow/density curve. Kinematic wave which is the overall motion may cut across the two sections of the flow/density curve. Therefore it would be misleading to describe a wave across the two sections for flow/density curve as shockwave. Since rarefaction wave is merely an expansive density loss, it would be restricted to the constrained section. Traffic flow shock waves are formed when there is a discontinuity of flow on a highway section. This discontinuity arises from abrupt changes in density as a result of a disturbance to the flow. Disturbances to traffic may be due to internal or external sources.Traffic stream with platooning effects can invoke the use of kinematic wave. Afteralla wave is the propagation in time (*t*) and space (x) of a disturbance in a medium. By investigating the presence of kinematic wave in the traffic stream, one is merely stating the obvious; that the outcome of the study could be traffic stream rarefaction and/or traffic shockwave. Drivers experience 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. Kinematic wave theory was proposed jointly by Lighthill and Whitham [4].Roads are designed to Malaysian specifications [5]; traffic shockwave propagations on these roads will not be any different from anywhere else.Shockwaves are transition zones between two traffic states that move through a traffic environment like, as their name states, a propagating wave.Kinematic model is made up of three components: the fundamental diagram, the conservation equation, and initial conditions. Where density is defined as $\rho\ (x,t)$ and flow is $q(x,t)$ then, $x_2 > x > x_1$: Integrating over an arbitrary time interval,$[t_1, t_2]$

$$\int_{x_1}^{x_2}\left(\rho\left(x,t_2\right)-\rho\left(x,t_1\right)\right)dx=\int_{t_1}^{t_2}\left(q\left(x_1,t\right)-q\left(x_2,t\right)\right)dt$$

This is equivalent to $$\int_{t_1}^{t_2}\int_{x_1}^{x_2}\left(\frac{\partial \rho}{\partial t}+\frac{\partial q}{\partial x}\right)dxdt=0$$

Therefore the integrand equation 1 is the Conservation Law [6]. It is the fundamental law governing the kinematic Wave Model.

$$\frac{\partial \rho}{\partial t}+\frac{\partial q}{\partial x}=0 \qquad (1)$$

If q and ρ is assumed to be $q = Q(\rho)$; Then $\rho_t + c(\rho)\rho_x = 0,\ c(\rho) = Q'(\rho)$

Plug discontinuities into the solution by a simple jump in q and ρ assuming q and ρ are continuous; $x_1 > x > x_s(t), x_s(t) > x > x_2$ Then;

$$q(x_{2,}t)-q(x_1,t)=\frac{d}{dt}\int_{x_2}^{x_s(t)}\rho(x,t)\,dx+\frac{d}{dt}\int_{x_s(t)}^{x_1}\rho(x,t)\,dx$$

$$=\rho(x_s^{-},t)s-\rho(x_s^{+},t)s+\int_{x_2}^{x_s(t)}\rho_t(x,t)\,dx+\int_{x_s(t)}^{x_1}\rho_t(x,t)\,dx$$

Where: $\rho(x_s^-,t), x \rightarrow \rho(x_s^+,t)$are the values of$\rho(x,t), x \rightarrow x_s(t)$ (2)

The statement is also supported by Khisty and Hall [7]. They also presented traffic shockwave propagations as function of congestion and queuing.Most applications of the model concentrated on traffic congestions from signalised intersections. Because of inherent traffic flowrate detection weakness the model has been severly criticised in previous studies. Notwithstanding, the model has been used extensively to explain traffic states and the length of queues along road segments and also in different traffic flow contexts. For instance, Xinkai et al. [8] derived the traffic trajectories of four major shock waves using the model.Yan Qui et al. [9]. also applied traffic shock wave theory to study the impact of large trucks on an expressway. Alicaet al. [10] studied the effect of aggresive driving on formation of traffic congestion using Lighthill Traffic shockwave theory. Also Wen-Xing and Rui-Ling [11] investigated the effects of highway slopes on the stability of traffic flows using the Richard's model. Duret et al. [12]. examined the onset of traffic congestion due to low-speed merging maneuvres in the traffic stream by use of shock wave theory. Ngoduy [13] used the continuun theory and applied the multiclass approach to display the widely scattered flow–density relationship caused by random driver behaviour. Qiaoru et al. [14], relying on traffic shock wave theory studied the influence of moving bottleneck caused by large trucks in the traffic stream through simulation with VSSIM software. Hani and Rahim [15] analysed queue formation and dissipation in work zones using the shock wave theory. Richards] [16] who worked separately from Lighthill and Whitham also proposed kinamatic wave theory that was used by Wen-Xung and Rui-Ling. Suzuki and Matsunaga [17] evaluated the safety of platooned vehicles based on shock wave theory. The range of applications of shock wave theory on highway segements can therefore be extensive. According to wikibook [18]

‘Shockwaves are byproducts of traffic congestion and queueing. So, it can be postulated that if kinematic wave is a mere motion and shockwave propagations are function of congestion and queing then they are clealy different. In any case,kinematic wave is a family of parallel characteristics in the x-t plane. Kinematic wave (k_w) can be computed as:

$$k_w = \frac{q_c - Q_B}{k_c - k_B} \tag{3}$$

2.1 Shockwave

It is a formation of an abrupt change in traffic stream with compressive characteristics that will trigger temporary congestion. Traffic shockwave is a function of flow/density relationship. Lighthill and Whitham [4] postulated that there exists some functional relationship between flow and density that may vary with location but not with time. Where location is *x* and time is *t*; then

$$k(x,t) = k\ (q(x,t), x) \tag{4}$$

If it assumed that there is no vehicle entering or exiting the traffic stream, then the equation of continuity can be applied to equation 8 to give a partial differential equation 7 for q (x, t).

$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial k(x,t)}{\partial t} = 0 \tag{5}$$

This is an exaggerated assumption, nonetheless;

$$S_{w(q(x,t),x)} \frac{\partial k(x,t)}{\partial t} + \frac{\partial k(x,t)}{\partial t} = 0 \tag{6}$$

$$S_w(q,x) = \frac{\partial k(q,x)}{\partial q} \tag{7}$$

Should the lead driver brake abruptly due to changes in traffic, roadway, weather or ambient conditions the resultant kinematic wave will operate along lines C, A and Bas shown below in Fig. 1. However, traffic shockwave speeds will operate between A and B; as shown in Fig. 1. So care should be taken when expressing traffic kinematic so as not to misconstrue it as traffic shock wave propagation. They are clearly not the same thing. The area of traffic shockwave (s_w) in Fig. 1 can be taken as:

$$s_w = \int_{k_A}^{k_B} f(k)\,\partial k = ak^2 + bk - c \tag{8}$$

For $k_A < k \geq 0.85q$; Else $S_w = 0$

$$f(k) = ak^2 + bk - c$$

2.2 Rarefaction Wave

-It is the effect that the kinematic profile with diverging characteristics has thinned out over time. In essence rarefactions are post shockwave formations, keep in mind that shockwave is a post capacity kinematic wave. Rarefaction can occur in circumstance where traffic change is spread across the stream simultaneously, for example at the onset of rainfall or snow. However, rarefaction expansion is limited to pre-capacity section of the flow/density curve shown in Fig. 1. As mentioned earlier, traffic shockwaves are by-products of congestion and queuing [4] whereas rarefaction waves are merely the kinematic effects that thin out over time. In order words rarefaction faction (Rw) will operate between C and A (see Fig. 1); hence

$$R_w = \frac{q_c - Q_A}{k_c - k_A} \quad \text{For } k_A \geq k \geq 0.85q\text{; Else } R_w \rightarrow S_w \tag{9}$$

Since our interest is in estimating the traffic kinematic wave, the choice of precise value of critical density need not be very critical to the study outcome. So, it may be postulated that road hump can cause traffic kinematic waves. The waves may be strong enough to send shock through the traffic stream or it may be mere rarefaction wave. If the assertion that, 'traffic shockwaves are post capacity products as suggested in the paper is to hold, then congested traffic flow and density must be in temporary congestion. Therefore, a threshold capacity must be estimated in other to ascertain whether traffic shockwave has indeed occurred. Where the threshold capacity has been exceeded the passenger car equivalent values being an instrument of capacity computation must also be modified. Ignoring PCE modifications could lead to grossly inaccurate road capacity with consequences for modeling. Therefore care should be taken when expressing wave in traffic in order not to misrepresent one for another.

2.3 Data Collection

In order to determine impact of road hump (RH) on traffic kinematic wave, 'with and without' RH impact studies were undertaken at selected sites in Skudai, Malaysia. The basic criteria for selection among others are that; sites must have straight section, flat terrain, and good pavement surfaces. The geometric shape of roads, height of road hump, pavement conditions and other environmental factors also were taken into account in selecting the study site to avoid biases. In addition traffic flow must not be influenced by factors such as petrol stations, bus stations, mosques, intersections, traffic signals and parking. Sites are divided into two sections A (free flow section) and B (hump constrained section) as shown below in Fig. 3. Section A is set 110m from the hump. Note that section A must be set at a distance greater than SSD so as to minimise the influence of road hump on drivers' reaction as they approach the barrier. The distance is computed from stopping sight distance (SSD) equation 10; assuming reaction time to be 2.5s and deceleration rate to be $3.4 m/s^2$. Automatic traffic counters (ATC) were installed on the road sections as shown in Fig. 2. Two pneumatic tubes were set at one meter apart across the carriageway lane width and connected to an automatic recorder. 24-hr traffic volume, speed, headway, and vehicle type data were captured per section continuously for twelve weeks. Random periodic hourly manual traffic counts were carried out to check reliability of traffic data captured by ATC. Three types of vehicles private car, light truck (4.8 and 11.1m length) and heavy trucks>11.1m length were identified. Traffic stream data per section per site for working days (Monday-Friday) under dry weather, daylight conditions were collated into peak and off-peak traffic stream data. Average traffic stream weekly peak and off-peak data were determined and bunched into twelve (one per week). Then, twelve peak hour traffic stream flow and corresponding speed data from section A were used to determine the base traffic flow rate pattern. Twelve off-peak hourly traffic stream flow and corresponding speed data per site per section were used to develop flow/density function.

$$SSD = 0.278vt + \frac{0.039v^2}{a} \tag{10}$$

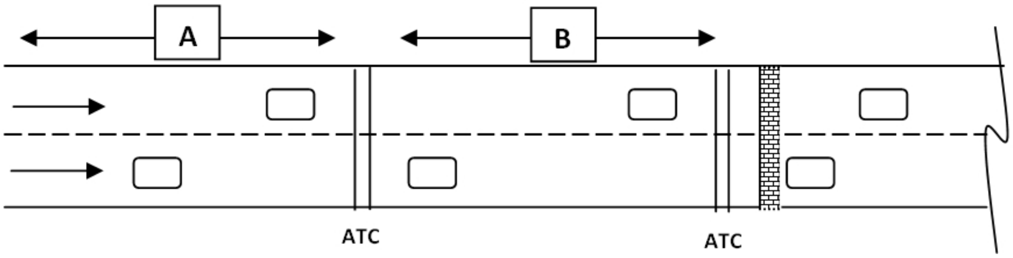

Fig. 2. Typical layout of impact study site

3. RESULTS AND DISCUSSION

Traffic stream peak data for road hump zone were analyzed in order to estimate the base traffic flow and density performance criteria of the road section under observation. The paper used off peak traffic data for comparative assessment of kinematic waves so as to remove the effect of peak travel from the estimated outcomes. As shown below in Fig. 3 and illustrated in Fig. 4, the base traffic flow data (q_B) was computed as:

$$q_B = -0.51k^2+74.6971k-1010.6 \tag{11}$$

$$\frac{\partial_q}{\partial_k} = -1.02k + 74.697 = 0; hencek \approx 73$$

Plug k into the model equation11,

Capacity Q_B = 1725pcu/h.

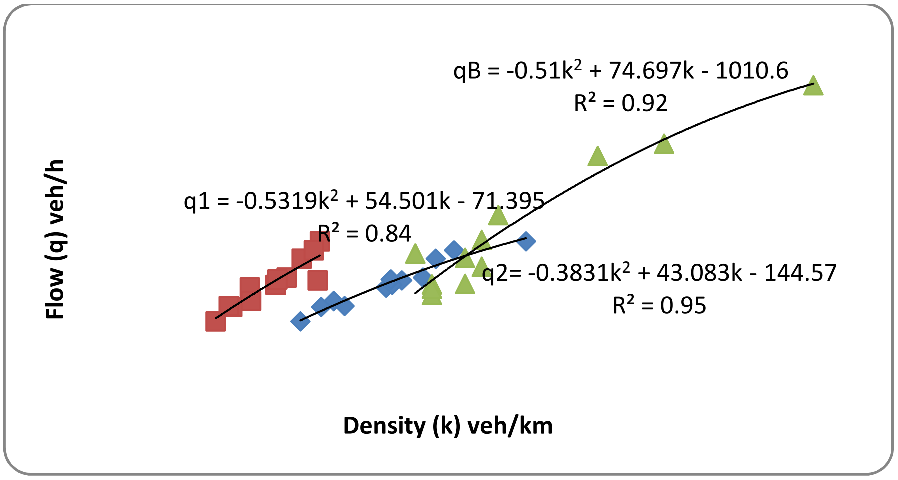

Fig. 3. Typical flow/density model coefficients

Note: Red (q1=without RH); Blue(q2=with RH); Green (qB=base flow rate)

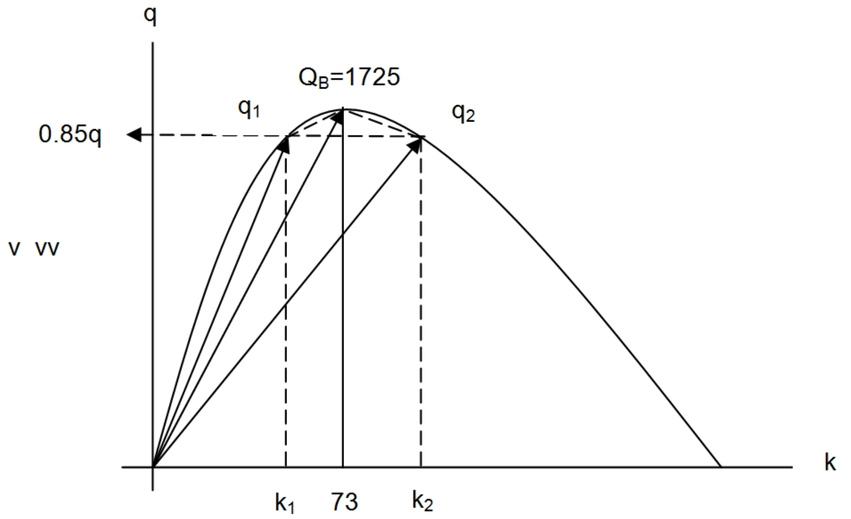

Fig. 4. Estimated Base Parameters

The model equations have the correct signs, and for each case study model coefficients shown above in table 1 were statistically tested for reliability. Coefficients of determination R^2 shown that equations are acceptable for prediction, t-test (>3) results show that the independent parameters are useful and the F- Statistics>5, show that the model equations did not happen by chance. Typical results from the model coefficients are shown below in Table 1.

Table 1. Model Coefficients and coefficients of determination

Case	q_1	R^2	q_2	R^2
1	$-0.5319k^2+54.501k-71.395$	0.84	$-0.3831k^2+43.083-144.57$	0.95
2	$-0.4226k^2+35.042k-22.851$	0.91	$-0.5905k^2+48.545k-22.698$	0.96
3	$-0.6519k^2+54.071k-41.607$	0.75	$-0.3692k^2+41.752k-120.67$	0.93
4	$-0.7137k^2+48.86k-169.255$	0.96	$-0.4232k^2+46.944k-6.9547$	0.97

Note that in Fig.4 above speed (v) is the slope of flow (q) and density (k) it increases from q_1 to Q_B and decreases thereafter because of capacity restraint. Traffic flow oscillates from zero to Q_B and flow rate contracts thereafter to zero. The difference in traffic flow behaviour partly explains why kinematic wave is not the same as traffic shockwave. In any case the base flow rate in figure 4 is 1725pcu/h; it has a corresponding critical density of 73veh/km meaning that the critical density of 73veh/km must be exceeded for traffic shockwave to occur on the surveyed road sections. The base flow rate is absolutely crucial when determining traffic shock wave because it will show whether road capacity has been reached and/or exceeded. The beginning of traffic shock wave in Fig. 4 is at Q_B and it will terminate at $q_{2.}$ Should traffic kinematic waves occur they will start from q1 and end at q2

It has been mentioned earlier that traffic shockwave can be construed as temporary congestion, further that in the flow/density curve and indeed its subordinate speed/flow curve, speed oscillate at the unconstrained section often called free flow of the curve. Whereas traffic flow contraction and expansion occur at the constrained section of the curves and it is this behavioural change that will trigger shock in the traffic stream. In all cases shown below in Table 2, there is no evidence of traffic kinematic, rarefaction or shock waves whatsoever. That can be attributed to two factors namely; sufficient forward visibility and pre-hump warning signs.

Table 2. Traffic kinematic, shock and rarefaction waves

Case	q_1	Q_B	q_2	k_1	k_B	k_2	K_w	S_w	R_w
1	1325	1725	1063	51	73	57	0	0	0
2	1267	1725	976	42	73	42	0	0	0
3	1069	1725	1074	45	73	58	0	0	0
4	672	1725	1298	35	73	56	0	0	0

Note - $K_w=q_2 - q_1 / k_2 – k_1$; $S_w=q_2 – Q_B / k_2 – k_B$; $R_w=Q_B – q_1 / k_B – k_1$;
Provided $k_2>k_B$, *Else* $K_w=S_w=R_w = 0$:

4. CONCLUSION

The differences between traffic kinematic wave and shockwave were highlighted and discussed in the paper. The paper has shown that traffic kinematic waves can occur without triggering traffic shockwaves and further that rarefaction waves are reverse kinematic waves. Rarefaction waves occur when kinematic wave propagations terminate. Based on hypothesis that 75mm road hump cannot be called solely to account for traffic kinematic wave; traffic flows and densities for road sections with and without hump were computed and compared. The synthesis of evidence from the study show that road hump did not trigger kinematic in all four case studies; consequently the paper concludes that the hypothesis that road hump will trigger traffic shockwave is null and void; it is more likely to be driver's error, poor judgment or sheer reckless driving.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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