Exploration of Trapezoidal Flowrate Contractions Resulting from Pavement Distress

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Abstract
Highway traffic theory is concerned with the movement of discrete objects in real time over a finite network in 2 Dimensions. It is compatible with or dependent on fundamental diagram of traffic. Highway capacity is the apex point of the flow and density curve. The flow and density curve is asymmetric. It has 2 chambers (unconstrained and constrained). Obviously the constraint is capacity. The extent of highway capacity loss depends solely on the degree of traffic flowrate disturbances. Trapezoidal flowrate contraction is a description of the rate of flowrate forward movement within the constrained chamber of flow/density curve. A capacity estimation method was used that is based on extrapolation of the free flow part of the fundamental diagram representing flowrate and density in a ‘with and without pavement distress’ impact study in Skudai Malaysia. The method applied assumes that the density at capacity is not affected by road distress which implies that capacity losses are fully the result of speed changes. Capacities for two directions of one road section were estimated and compared. Results show that capacities for road section with good and distressed surfaces differ significantly and trapezoidal flowrate contraction ranges from 4m/s to 11m/s depending on the degree of capacity loss.

Keywords: trapezoidal flowrate contraction, capacity loss, speed changes, fundamental diagrams, pavement distress

INTRODUCTION
Highway traffic flow has always been presented in many ways. In some literatures, hydrodynamics concepts have been applied, others favour Greenshield’s method. Without question traffic flow is an essential quantitative parameter that is constrained by density. Mathematicians have often found traffic stream a useful scenario to model based on the fluid mechanics. Traffic stream in neither liquid nor gas, more importantly it does not respond to roadway geometry same way fluids would respond to the configuration of their containers. Highway traffic theory is concerned with the movement of discrete objects in real time over a finite network in 2 Dimensions. It is compatible with or dependent on fundamental diagram of traffic. Highway capacity is the apex point of the flow and density curve. The flow and density curve is asymmetric. It has 2 chambers (unconstrained and constrained). Obviously the constraint is capacity. Traffic flows within the unconstrained chamber oscillates relative to speed changes, whereas flowrate (capacity) in the constrained chambers contracts relative to speed changes. Traffic, roadway and ambient conditions are known factors that affect highway capacity. Trapezoidal flowrate contraction concept is still a novelty in transportation engineering. It measures flowrate contractions resulting from highway capacity loss. It is named trapezoidal flowrate contraction (TFC) because of its geometric shape and the study is interested to find out the consistency of the shape irrespective of the causation of highway capacity loss. TFC under traffic and rainfall conditions have already been explored, the focus is now pavement distress. Pavement distress is a function of vertical depression (potholes) or deflection (road humps and speed cushions). Specifically, pothole is an open cavity in road surface with at least 150mm diameter and at 25mm depth. Vertical deflections are traffic calming (road safety) devices aimed at reducing vehicle speeds. Although they are effective deterrent to speeding motorists, nonetheless they give discomfort to drivers and their passengers because of the need to climb and descend at every installation. A special focus of the paper is the comparative results of trapezoidal flow contraction resulting from road humps to that of pavement distress. The objectives are; to determine the extent of trapezoidal flow contraction rates resulting from potholes and road humps under daylight and dry weather conditions.

CONCEPTS OF TRAPEZOIDAL FLOWRATE CONTRACTION
Poor road surfaces are not only recipes for congestion and road accidents; they are characterized by slower speeds, longer travel times, increased queueing and
severe discomfort. Potholes, edge subsidence, and vertical deflection (speed cushions, humps, and speed tables) are examples of pavement distress. The paper is not about how these distresses were acquired; rather it focused attention on the performance of traffic stream traversing them. Capacity which is central to traffic analysis can be taken as the maximum traffic flowrate traversing a point or uniform section of road carriageway lane per hour under prevailing conditions. When a highway is oversubscribed, flowrate reduces and capacity loss is recorded. As perturbation sets in, drivers are no longer free to choose speeds or change lanes freely; sometimes frustration may give way to anger and in some cases road rage. In any case, capacity of any roadway follows a probability distribution depending on headways and speeds between vehicles. It can be measured directly if the road section in question is a bottleneck where capacity is frequently reached or it can be estimated by extrapolating free flow observation in cases where road section do not form a bottleneck. In order to get reliable results, it is desirable that flows be near capacity. Trapezoidal flow contraction is function of highway capacity loss. In other words, highway capacity loss must occur for TFC to be relevant. TFC is a measure of traffic flow contraction rate attributable to the magnitude of prevailing conditions, thus if highway capacity loss is severe say, then traffic flow contraction rate would be high and vice versa. Trapezoidal flowrate contraction has not been the subject of much research; most studies on highway capacity are restrictive to the traditional boundary of fundamental diagrams. Others explore the concept of hydrodynamic traffic modeling.

Hydrodynamic models rely on incompressibility of flow that is to infer that object in a network are of finite length. But then do you treat traffic mix as a singular object. Vehicles on highway travel at finite velocities, varying from vehicle to vehicle and time to time. Drivers may choose to overtake or pass or be contended to stay behind the lead vehicle, keep in mind that resistance to the passage of vehicles varies throughout the network. Bozani and Mussane (2005) proposed driver’s behaviour theory based on the law of mass conservation. The model has little resemblance to traffic stream realities. Firstly, modeling driving behaviour would suggest that subjective psychological parameters be introduced. That did not happen. Secondly, the law suggests that inflow, outflow and mass storage in the system must be in balance. This does not apply to highway. The fundamental diagram of traffic flow shown below in figure 1 will be explored.

\[ q = \frac{u k}{\chi} \Rightarrow \chi = \frac{q}{u} \]  

(1)

Speed and density as contained in many literature has been shown to have a linear relationship, where;

\[ U = u_\text{f} - \frac{u_f \chi}{k} \]  

(2)

If equation 2 is plugged into 1 then flow and density quadratic equation 3 can be used to estimate highway capacity. In the relationship, density acts as the control parameter and flow the objective function and could be written as:

\[ \phi = u_\text{f} k - \frac{u_f \chi}{k} \]  

(3)

In theory, where the flow / density relationship has been used to compute roadway capacity, Minderhoud et al (1997) Ben-Edigbe (2005, 2010), Van Arem (1994); the critical density is reached at the apex point as shown in Figure 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 flowrate is operating under constrained condition. The slopes, \( q_{in} \) and \( \gamma \) correspond to optimum speeds if equation 1 is to hold and the slope \( \chi \) represent average operating speed.
The shape of the enveloped area $q(k, y)$ to $y_k$ is trapezoidal hence the ellipse – TFC meaning ‘Trapezoidal Flowrate Contractions’. Consider Equation 3 again where;

$$q = u_f k - \frac{u_f^2}{k_c} k^2$$

For maximum flow;

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

Then, critical density $k_c$

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

Plug $k_c$ into equation to estimate capacity,

$$C = \left( \frac{u_f}{2 \left( \frac{u_f}{k_c} \right)} \right)^2 - \frac{u_f^2}{k_c} \left( \frac{u_f}{k_c} \right)^2$$

(4)

It may be the case that such calculated capacities are unrealistically high and questionable. It can even be argued that capacities derived in such a way may have very little resemblance to traffic actuality. Since our interest is in estimating the capacity change due to pavement distress, the choice of precise value of critical density need not be very critical to the outcome of this study.

DATA COLLECTION
The paper is concerned with operational capacity based on direct-empirical method using observed volumes and speeds to derive densities. The road section used for the study was not a bottleneck; hence extrapolation of the free flow part of the fundamental diagram representing flowrate and density was used. From observation at surveyed sites, trucks are less affected by pavement distress than passenger car and it may be argued that the passenger car equivalent values of trucks or Heavy Goods Vehicle (HGVs) are somewhat lower than those of passenger cars on roadways with significant pavement distress. Notwithstanding, the method adopted in estimating PCE will have no effect on the outcome of the study (Ben-Edigbe, 2010). A simple headway method was used to derive PCE values for the section with and without road distress. The calibration of the PCE values can have a significant impact on capacity analysis computations (Seguin et al, 1998). The effects of pavement distress on passenger car equivalent values are significant and must be taken into account when determining flow at road section with pavement distress. So, within the purview of the objectives of the study and the study boundary, roads were selected based on the following criteria:

Road Link ≥ 500m to allow for survey length > 210m, surface distress length (variable) and transition length = 130m after road humps. Appropriate road hump heights and spacing needed to achieve mean ‘after speeds are shown in Tables 1 & 2.

Study sites were divided into three sections with Section A as the upstream end and Section C the downstream end, while Section B was the transition section. Roadway at section A is without humps or potholes as the case may be, at section C road humps are spaced at 60m intervals whereas potholes have no defined patterns but were grouped together. Section B was set at 130m from the baseline of section A and B. Three types of vehicles were distinguished: passenger car, light and heavy vehicles. Surveyed sites 1 and 2 have variable pothole depths, diameters, numbers and length. Whereas surveyed sites 3 and 4 with 75mm round top hump type spaced at 60m intervals

ANALYSIS AND DISCUSSION
Stepwise procedure used for estimating road capacities and trapezoidal flow contractions in the studies can be stated as follows:
Step 1 Determine flow, speed and density using appropriate PCE values
Step 2 Determine variances and standard errors
Step 3 Derive flow/density equations from speed density linear equation and skip step 4, or
Step 4 Use flow/density relationships to determine flow/density model coefficients
Step 5 Test model equations for validity
Step 6 Estimate critical densities by differentiating flow with respect to density
Step 7 Determine roadway capacities by plugging estimated critical densities into model equations
Step 8 Determine roadway capacity loss and the corresponding trapezoidal flow contraction rate. To obtain the total loss area A under the polygon

$$A_a = \frac{1}{2} h(q_{a-1} + q_a)$$

Example of Capacity loss ($C_L$) and TFC estimation,

$$q_{a} = -0.5079 k^2 + 50.26 k - 39.48$$

$$\frac{\partial q}{\partial k} = 2(-0.5079k) + 39.48 = 0; \text{therefore critical density,}$$

$$k_c = 50 \text{ veh/km}; q_{k} = -0.5079(50)^2 + 50.26(50) - 39.48; = 1204 \text{ pcu/hr}$$

Optimum speed, $u_o = 120/50 = 24 \text{ km/h}; C_L = (1555-1204) / 1555 = 22.5\%$

Where $h=22\text{veh/km}, q_k = 1555 \text{pcu/hr} and q_{a-1}=1204 \text{pcu/hr}$

$$A_a = 11(1555+1204) = 30,349$$

Rate of change (TFC),

$$\frac{30.349-30.349}{h} = 4.43 \text{m/s}$$

The methods used for estimation of the model coefficients are ordinary and constrained least square regressions. For each case capacity was estimated for a fixed critical density. As shown in Tables 1 and 2,
at road sections with pavement distress, maximum speed is somewhat less than the optimum speed at road sections without pavement distress. The vehicle speed oscillation is still within the trapezoidal flow contraction envelope, take for example site 1; free flow speed is estimated to be about 124km/hr and the optimum speed is 55km/hr, however, once the pavement distress impact is factored in, optimum speed dropped to 24km/hr. The remainder of findings are summarised in tables 1 and 2 below. In sum the study showed that reduction in vehicle speed would result from pavement distress.

<table>
<thead>
<tr>
<th>case</th>
<th>estimated coefficients</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1 with potholes</td>
<td>39.438 50.26 0.5079 0.96</td>
<td></td>
</tr>
<tr>
<td>Site 1 without potholes</td>
<td>177.83 123.98 0.2180 0.87</td>
<td></td>
</tr>
<tr>
<td>Site 2 with potholes</td>
<td>186.32 59.133 0.5283 0.94</td>
<td></td>
</tr>
<tr>
<td>Site 2 without potholes</td>
<td>99.337 113.35 1.8229 0.92</td>
<td></td>
</tr>
<tr>
<td>Site 3 with road hump</td>
<td>0 46.489 0.4326 0.70</td>
<td></td>
</tr>
<tr>
<td>Site 3 without road hump</td>
<td>0 75.343 0.7627 0.68</td>
<td></td>
</tr>
<tr>
<td>Site 4 with road hump</td>
<td>0 60.846 0.5307 0.50</td>
<td></td>
</tr>
<tr>
<td>Site 4 without road hump</td>
<td>0 81.012 0.8152 0.55</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>case</th>
<th>capacity pcu/hr</th>
<th>critical density</th>
<th>optimum speed</th>
<th>capacity loss %</th>
<th>TFC m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1 with potholes</td>
<td>1204 50 24 22.5</td>
<td>4.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 1 without potholes</td>
<td>1555 28 55 0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 2 with potholes</td>
<td>1328 57 23 28.2</td>
<td>5.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 2 without potholes</td>
<td>1846 32 58 0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 3 with road hump</td>
<td>1254 54 23 32.7</td>
<td>11.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 3 without road hump</td>
<td>1866 39 48 0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 3 with road hump</td>
<td>1746 57 30 13.2</td>
<td>3.69</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 3 without road hump</td>
<td>2012 37 54 0</td>
<td>0</td>
<td></td>
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</tbody>
</table>

Note: TFC – trapezoidal flowrate contraction rate

CONCLUSION

Based on the synthesis of evidences obtained from the relationship between roadway capacity and pavement distress it is correct to conclude that no lasting solution to the challenges that face traffic flows will be found unless that solution takes account of the vexing issue of trapezoidal flowrate contractions. Based on the findings of the study, it can be concluded that:

1. There is a significance change vehicle speed between the ‘with’ and without pavement distress sections.
2. Reduction in roadway capacity was attributed to pavement distress prevalent per surveyed road length per carriageway lane or road humps spaced at 60m interval.
3. Notwithstanding, the hypothesis that trapezoidal flowrate contraction would result from pavement distress remains valid.

REFERENCES


