GIS and GPS to Evaluate Urban Arterial Performance

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ABSTRACT

New performance-based design procedures with the incorporation of operating speeds were proposed utilizing Global Positioning System (GPS) and Geographic Information System (GIS) technologies for arterial performance evaluation and congestion quantification at urban areas. The relevance of geometrical variables and land use to operating speed was also investigated using consistency measure. The collected variables in the data-base layers of GIS included: traffic volume, pedestrian volume, parking occupancy rate, cross-section characteristics, geometry of road, road environment features and land use for arterials and relevant intersection layers. The results showed that: 1) Consistency could provide a new performance measure of urban streets utilizing GPS data incorporated with GIS capability; 2) Divided ring road arterials which have more length, more than one lane and are located at residential areas were more consistent with their posted speed limits than the others; 3) Congestion can be quantified using a new scheme proposed in this research work utilizing GIS and the second-by-second GPS data.

KEYWORDS: GIS, GPS, Arterial performance, Evaluation.

INTRODUCTION

In the past, adding capacity was considered the main solution to eliminate or reduce travel delays. However, this approach has frequently proved to be insufficient. Faced with this reality, many urban areas have opted for implementing alternative management measures. Moreover, new technologies including GPS, GIS and computer vision should have a role in data collection, spatial analysis and display.

However, because GPS receivers record location as longitude-latitude pairs, additional tools are required to provide a linear reference to these point locations. Fortunately, GIS can be used for this purpose, with the added value that the resulting travel time data can be entered directly into existing geographic databases to find the fastest and shortest path along arterial networks as well as to evaluate arterial performance and conduct improvement for congested segments and failed intersections.

Early efforts to measure roadway performance focused on the arterial system using stationary equipment, such as inductive loop detectors and closed circuit television (CCTV) cameras. Thus, recent research has demonstrated the feasibility of using GPS and GIS technologies for automating travel time data collection, reduction and reporting when using a probe vehicle (Quiroga and Bullock, 1998; Quiroga, 2000). The new automated procedures provide consistency, automation, better levels of resolution and better accuracy in measuring travel time and speed than traditional techniques do.

Many research studies considered consistency a major component to evaluate safety on rural highways. In this research work, consistency on urban arterials was studied; i.e., the degree of uniformity between

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design speed and operating speed of the segments to evaluate the performance of roadways. Consistency was crucial to correlate geometrical elements with operating speed and how it would affect vehicle speed and delay. Geometrical and operational elements have an effect on the flow and delay of traffic; therefore, characteristics of consistency are vital to control delay and travel time.

The objectives of this research were to utilize GIS and GPS to measure travel time, operating speed and delay time for arterial congestion quantification as well as to utilize GIS as a tool to develop digital spatial maps for travel time, speed and consistency models for arterial performance evaluation at urban areas.

Table 1. Description of horizontal curve variables

Variable	Description	Unit
Radius	The radius of circular curve	m
Length	Arc length of curvature	m
LC	Length of chord, from the P.C. to the P.T.	m
D	The degree of curvature	degree
Def_angle	The angle of deflection or external angle of the curve	degree
T	Length of tangent from the P.C. to the P.I.	m
M	Middle ordinate distance	m
E	External distance	m
Tang_speed	Operating speed at approach tangent	km/h
Curvespeed	Average speed along the horizontal curve	km/h
Speed_Redu	Percent of speed reduction due to curvature	%

LITERATURE REVIEW

The National Performance Review (NPR) defines performance measurement as: “a process of assessing progress toward achieving predetermined goals, including information on the efficiency with which resources are transformed into goods and services (outputs)” (Martin, 2002).

Operational Measures

These measures are used to determine the operational characteristics of transportation facilities such as freeway and arterials. They include: flow, average speed, average travel time, number and percentage of stops, intersection delay, queue length and volume/capacity (V/C) ratio.

Planning Measures

These measures are used in the planning operations of the systems. They include:

- Acceptable delay (the threshold delay which the agency finds agreeable or which doesn’t necessarily harm the interests of public).
- Congestion index (the ratio of total arterial delay to arterial VMT).
- Travel rate (the ratio of travel time to segment length).
- Travel rate index (the ratio of travel rate on an arterial to the free flow travel rate).

Obaidat et al. (1997) developed a new methodology to evaluate the effect of roadway geometry of rural roads on highway traffic performance. Consistency measures were evaluated along sections depending on collected speed profiles using developed software package. They found that the curvature change rate had a great impact on speed consistency and that horizontal curve radius affected the speed profile and accident rate on the highway. They performed statistical analysis, indicating that hilliness, safety horizontal curves, degree of curvature, posted speed limit and stopping and passing sight distances were the most affecting variables to describe the consistency of roads.

Table 2. Arterial street network variables

Variable	Description	Unit
Direction	Direction of traffic flow	-
Function	Functional type of segment (arterial or ring)	-
No_Lane	Number of lanes of segment	Number
Type_secti	Section type (one-way or divided)	-
No_of_Hump	Number of humps along segment	Number
No_of_Open	Number of median openings along segment	Number
No_Roadcro	Number of road crossings along segment	Number
No_access	Number of access roads to segment	Number
Land use	Adjacent land use of segment (residential, commercial, industrial and university)	-
Speedlimit	Posted speed limit	km/h
Length	Length of segment	m
No_HC	Number of horizontal curves along segment	Number
Sec_Width	Width of segment	m
Med_Width	Width of median if divided	m
G	Average grade percent of segment	%
Parkrate	On-street parking rate of segment (0, low, mid and high)	-
Vol	Traffic volume in segment	veh/h
Ped	Crossing pedestrian volume	person/h
Avg_speed	Average operating speed along segment	km/h
Travel	Travel time along segment	sec
Maxspeed	Maximum recorded speed from GPS data	km/h
Speed Index	Ratio of travel speed to speed limit	-

Consistency of Arterial Design with Operating Speed

The policy on geometric design of highways and streets of the American Association of State Highway Transportation Officials (AASHTO) defines the operating speed as "the speed at which drivers are observed operating their vehicles under free flow conditions" and defines the design speed as "a selected speed used to determine the various geometric design features of the roadway". For a given design speed, the AASHTO (2004) guideline presents the design values for geometric elements such as stopping sight distance, minimum curve radius and length of vertical curve.

The policy on geometric design of highways and streets presents the design speed concept to provide a roadway with the consistency in design features that encourages most drivers to operate uniformly at their desired speeds. The design consistency refers to the following two concepts:

- For an individual alignment element, the roadway design should encourage most drivers to operate consistently with the intended function of the facility. That is; the operating speeds should be lower than the design speeds.
- For successive alignment elements, the roadway design should encourage most drivers to operate uniformly along the alignments. That is; the change of operating speeds between successive alignments should be less than some acceptable values.

The current design process begins with the selection of a design speed, which is determined by functional classification, speed limit, traffic volume, characters of terrain, adjacent land use and environmental factors. Fitzpatrick et al. (2003) found that the most important factors in selecting a design speed value were functional classification and speed limit. Once the design speed is selected, the AASHTO design policy presents minimum design values for geometric elements to incorporate safety factors. Designers can choose geometric characteristic above minimum values based on the terrain and economic constraints.

Several studies (McLean, 1979; Garber and Gadiraju, 1989; Krammes et al., 1994; Fitzpatrick, 2003) found disparity between operating speeds and design speeds. To explain disparity, many researchers have analyzed the limitations in the selection and application process of the design speed. Other studies have demonstrated that the design speed approach does not always result in operating speeds consistent with the intended speeds and functions of the roadways. Since drivers navigating the roadways neither know nor observe design speeds, they tend to drive at speeds that they consider comfortable and safe based on their perceptions of the roadway geometry regardless of the speed limit. Therefore, the overall speed of roadways may not be in agreement with the roadway's intended function.

Congestion Quantification

Congestion measures can be grouped into highway capacity manual (HCM) measures, queuing-related measures and travel time-based measures (Lomax et al., 1997).

There are three commonly used travel time-based measures: travel time, travel speed and delay. Travel time data collection is an integral component of traffic engineering studies. Travel speed and delay data can be derived from travel time data by using a reference desired/acceptable travel time or speed. Travel time-based measures are easy to understand by both the professional transportation community and the traveling public. They are flexible enough to describe traffic conditions at various levels of resolution in both space and time. This makes travel time-based measures appropriate for handling specific locations as well as entire segments. They also allow analysts to perform comparisons over long periods of time (e.g. years or decades). Travel time-based measures translate easily into other measures like user costs and can be used directly to validate planning models such as travel demand forecasting models (Laird, 1996). Travel time-based measures are applicable across modes. So important is travel time in this regard that the year 2000 edition of the HCM is being structured around travel time as a common measure of effectiveness for all modes. All these reasons make travel time-based measures extremely powerful, versatile and desirable. Not surprisingly, an increasing number of transportation agencies are switching to travel time measures to monitor and manage congestion. Therefore, they were used at this research work as the main planning and operation measures.

Data Collection

GPS vehicle tracking was used for the purpose of vehicle speed and travel time data collection containing vehicle location and speed at one second interval. The road environment data include roadway characteristics, cross-section features and adjacent land uses.

Three runs were used to measure travel time and operating speed for 20 arterials at Irbid City, Jordan which were segmented to 107. The collected GPS data records were overlain with a GIS digital road network map based on latitude and longitude information. This GIS layer could answer questions about the vehicle such as: where, when and how fast it was.

Each segment in arterial road had different road environment characteristics which were divided into:

1. Operational factors (traffic volume, pedestrian volume and parking rate).
2. Geometry characteristics (alignment of horizontal curves, cross-section characteristics and roadside features).
3. Adjacent land uses.

Traffic and pedestrian volumes were counted during spring time. Data was collected for working days (Monday through Wednesday) that represent the most common traffic and pedestrian conditions. Visualizing was used to estimate parking occupancy during vehicle tracking data collection for the three studied periods.

Common features that have a significant effect on travel time and speed profile were selected. They included:

1. Humps.
2. Horizontal alignment.
3. Median opening.

These features have important effect on drivers' speed profile and consistency of road design and operational speed. To locate speed humps along segments, GPS device was used to receive the coordination for each hump site, and then imported as vector layer at street network. Using the same methodology, the location of median opening was determined, and then median opening layer was established. The horizontal curve feature was drawn using aerial images that were registered and prepared by Irbid Municipality. The variables of horizontal curves simply related to the curvature characteristics such as radius, length of tangent, length of curvature, length of chord and degree of curvature were shown in Table 1. Data base of horizontal curves included the operating speed at the approach and reduction due to curvature.

Integration of GIS and GPS for Arterial Performance Analysis

Map Projection

The rectified images for Irbid City and all designed layers were projected into GIS at WGS-84 as a datum using Universal Transverse Mercator (UTM) coordinate system within 36N zone.

Layers Creation into GIS

The registered recreational map of Irbid City was used to digitize road features of selected major roads. These road features were selected based on consistency criteria. How these features will affect drivers' speed profiles and associated travel time was used as main criterion. Thus, road center lines, median opening, horizontal curves, speed humps and intersections at major road interceptions were the most important features used. The GIS layers created specifically for this research work included:

1. Arterial street map network.
2. Traffic controlled intersections.
3. Road environment features.

All road environment characteristics were entered for each segment, such as cross-section characteristics, operational characteristics, land use, travel time and delay variables. The travel time, travel rate, operating speed, delay and total delay attributes were very helpful for network creation to choose the fastest and shortest network path. Also, operating speed data can be used for congestion quantification and arterial performance evaluation. Table 2 demonstrates these variables and their units. After collecting GPS points using proposed vehicle tracking technique, these points must be transformed to GIS as layers in order to utilize them in performing spatial and consistency analysis.

GPS data base which includes travel time and operating speed will be used to evaluate the consistency of segments and CBD area.

Consistency Scheme

A new scheme has been developed to evaluate the consistency of urban streets using spatial analysis (GIS) for GPS data. The scheme followed the following steps:

1. Calculate speed index for each layer of GPS tracking points and add it as attribute.
2. Convert these layers from feature to raster for each studied time period based on the speed index attribute value.
3. Conduct the mean cell statistics for all tracking GPS layers associated to their time period.
4. Create the mean layer of all GPS raster layers using mean cell statistics.
5. Perform zonal statistics at spatial analysis to evaluate the consistency for the segments network based on the speed index variable using ID as zone field.
6. Repeat analysis like in step 5 according to (land use, function, section type, length and number of lanes) field zone.
7. Merge the segmented segments in the same arterial to evaluate the overall consistency for these arterials.
8. Perform zonal statistics to evaluate the consistency for arterial based on ID field zone.
9. Estimate the consistency of horizontal curves according to the length of curvature using the same steps followed above.

Congestion Quantification Scheme

The congestion level of the whole length of arterials was used as indicator for congestion using the GIS spatial analysis maps. A new scheme was developed to quantify congestion along arterials. In this scheme, the following steps were followed to quantify the congestion:

1. Apply speed index to quantify congestion.
2. Add speed index attribute to each layer of GPS tracking points.
3. Determine GPS points that have speed index less than 0.5 using query function.
4. Convert congested points in each layer to raster image.
5. Conduct mean cell statistics for all tracking GPS layers associated to their time period.
6. Perform zonal statistics at spatial analysis to calculate the summation of the speed index values for congested location at each arterial using ID as zone field.
7. Add new attribute to statistics result table which represents the percentage of congestion over the length of each arterial, calculated using the following formula:

*Congestion percent = (Sum of speed index value * Total length of arterials * 100%) / (Total number of GPS points at layer * Length of arterial).*

These schemes can provide a new methodology to evaluate the performance of arterial at continuous intervals.

ANALYSIS AND DISCUSSION

Optimum Path Selection Using GIS Network Analysis

Network analysis using GIS capabilities was conducted in this work to find the optimum path from the shortest distance and minimum travel time for the three study periods (8 am-12 pm, 12 pm-4 pm and 4 pm-8 pm). The results show that almost 50% of the optimum paths or routes that take less travel time were the shortest paths. This means that the shortest distance for route choice was not always the optimum path. This result was compatible with other findings that (47%, 36.3% and 38.8%) additional time was added to travel time if the route choice was the shortest distance. It can also be seen that travel time path between the O-D stations opposite to each other was higher than travel time of path between the adjacent ones, although the distance between adjacent O-D stations may be longer than the faced ones. This result confirms that the use of ring roads may take less travel time.

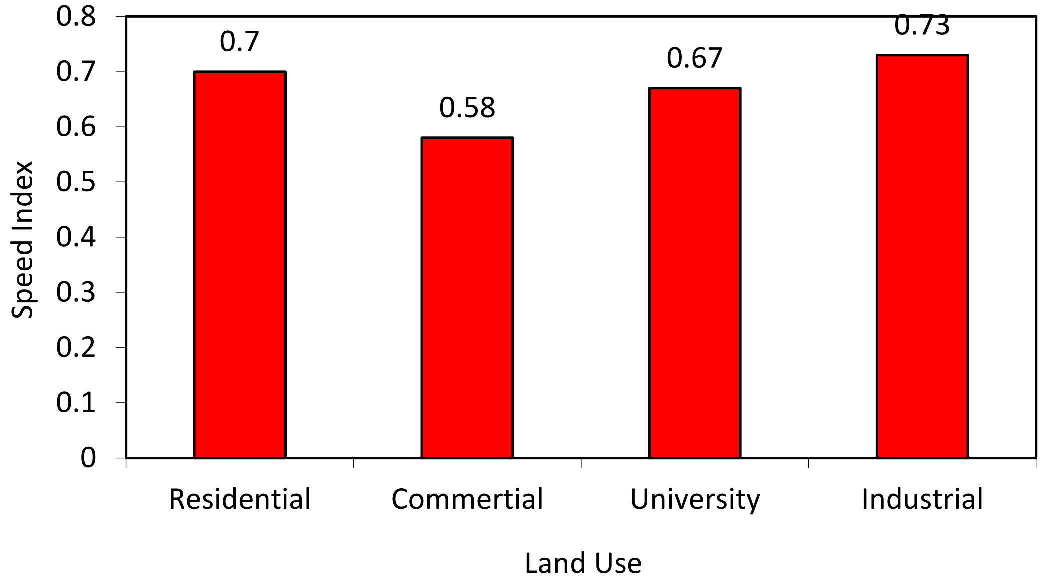

Figure (1): Consistencies of segments according to land use

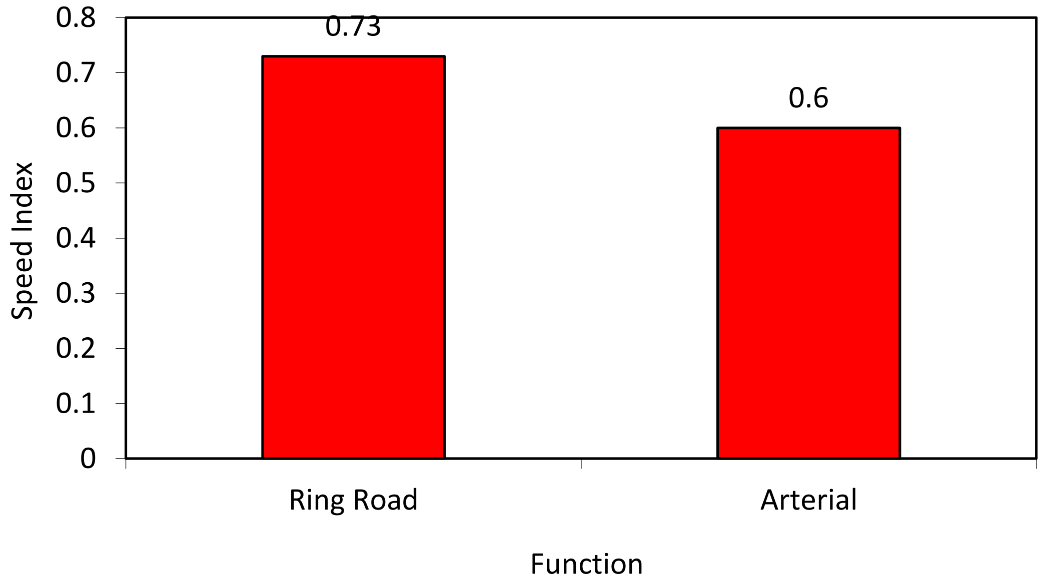

Figure (2): Consistency of segments according to their function

Consistency of Segments and Arterials

The consistency of segments was evaluated using zonal statistics from spatial analysis of GIS based on speed index value of the GPS points. The speed index could be used as an indicator for road environment consistency with speed design.

It can be observed that 23%, 65.4% and 11.6% of the segments have poor, moderate and good consistency using speed index scale of SI<0.5, 0.5<SI<0.8 and SI>0.8, respectively, while 0.6%, 68.4% and 21% of arterials have poor, moderate and good consistency, respectively. Obviously, there were less inconsistent arterials compared with inconsistent segments. The reason is that the arterial speed index was the weighted average of speed index for segments depending on segment length. Besides, an arterial may have segments with low speed index and other segments with high consistency.

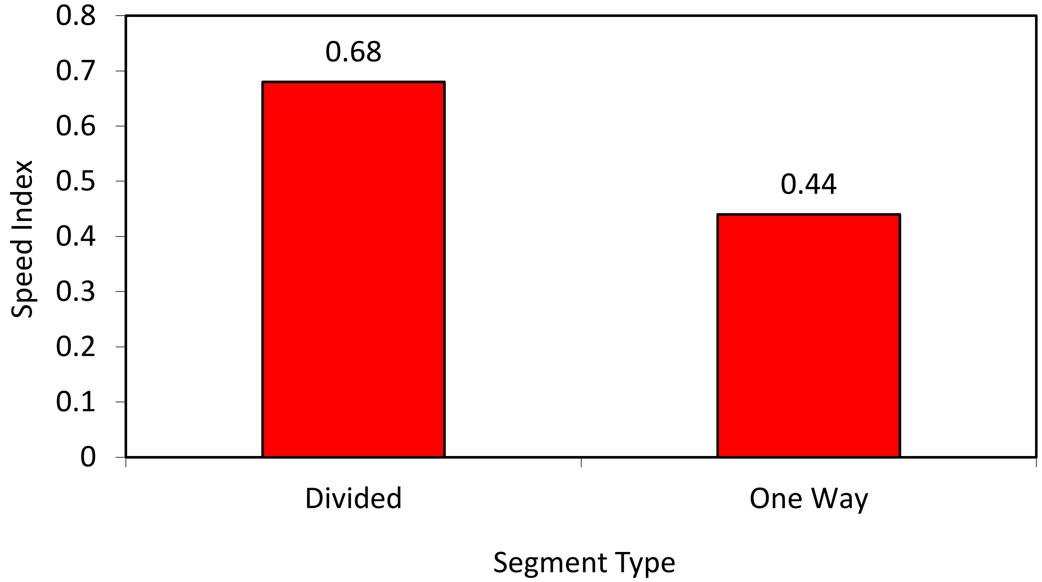

Figure (3): Consistency of segments according to segment type

Consistency of Segments According to Land use

Figure 1 shows the consistency of segments according to the adjacent land uses. It can be seen that segments located at commercial land use have the lowest consistency value. The reason behind this was that segments located at commercial areas had more parking maneuvers and higher pedestrian crossing. Thus, attention should be paid to offer pedestrian crossing facilities and off-street parking facilities.

Consistency of Segments According to Their Function

Figure 2 shows the consistency of segments according to their functions at arterials or ring roads. Arterials had less consistency than ring roads due to access points' complexity and traffic characteristics.

Consistency of Segments According to Segment Type

Figure 3 shows that divided segments were more consistent than one-way segments because most of the used one-way segments had one lane only.

Consistency of Segments According to Their Length

From Figure 4, it can be seen that longer segments were more consistent than shorter ones. In fact, longer segments may encourage drivers to increase their speeds to arrive at the intended destination. Equation (1) shows the relationship between segment length and speed index as a measure of consistency.

$$Speed\ Index = 0.181\ Ln(x) - 0.696 \quad R^2 = 0.51 \quad (1)$$

Consistency of Segments According to Number of Lanes

Figure 5 illustrates the consistency of arterials according to the number of lanes. The speed indices were 44%, 68% and 70% for arterials that had one, two and three lanes, respectively. The lowest speed index was for one lane, and the consistency of segment did not increase significantly if an additional lane was provided to segments with two lanes.

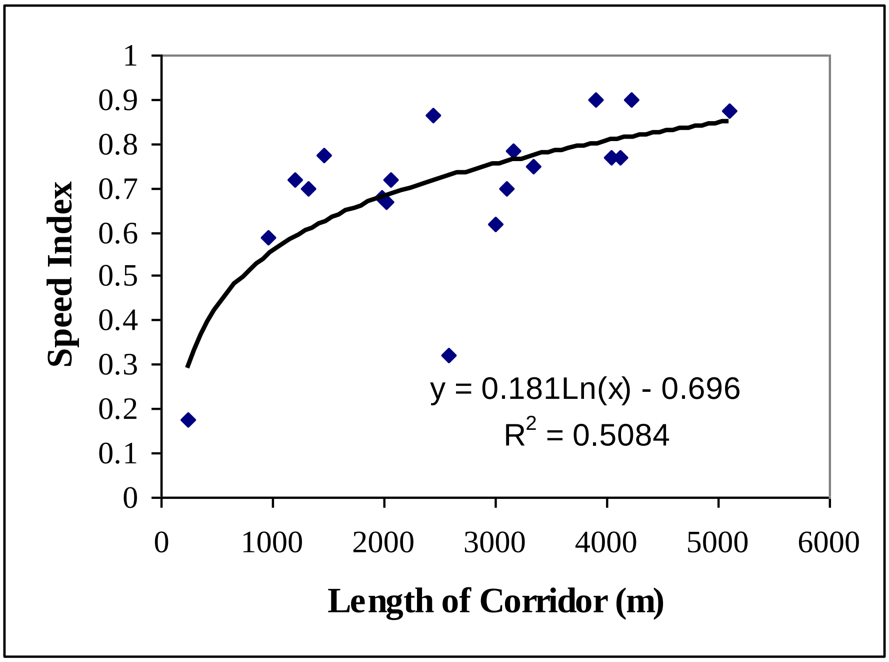

Figure (4): Consistency of segments according to their length

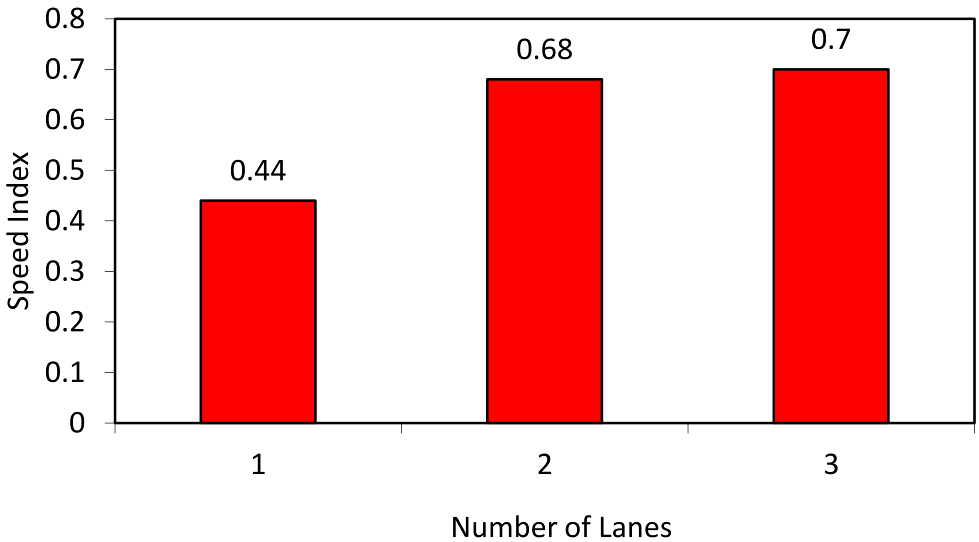

Figure (5): Consistency of segments according to number of lanes

Consistency of Horizontal Curves According to Curvature Length

Figure 6 shows the consistency of horizontal curves according to the length of curvature. It can be seen that the consistency of horizontal curves increased as the length of curvature increased. In other words, the length of curvature may affect the driver speed.

The minimum consistency of horizontal curves was 0.12 for a curve length of 40 meters. 30.4%, 30.04% and 39.2% of horizontal curves had poor, moderate and good consistency using a scale of SI<0.5, 0.5<SI<0.8 and SI>0.8, respectively. This is an indicator of using speed as a major factor of design for arterial curvatures due to road environment elements such as vehicles, pedestrians and sight distance.

Equation (2) shown below illustrates the relationship between the length of curvature of simple circular curves and speed index as an indication of consistency at horizontal curves.

$$Speed\ \ Index = 10^{-8}x^3 - 8\times10^{-6}x^2 + 0.0013x + 0.3138$$

$$R^2 = 0.56 \qquad (2)$$

Congestion Quantification

Congestion may appear in many locations of arterials, but the question is: what percentage along the arterial length is congested? The developed congestion quantification scheme was used to find the percentage of congestion along arterials. Figures 7 is an example of congestion quantification of arterials at peak period that shows the percentage of congestion of the total length of each segment. The average percentage of congestion for all arterials was (5.78%, 11.04% and 10.7%) for the three studied periods, respectively. The percentage of congestion might differ from a time period to another for the same arterial.

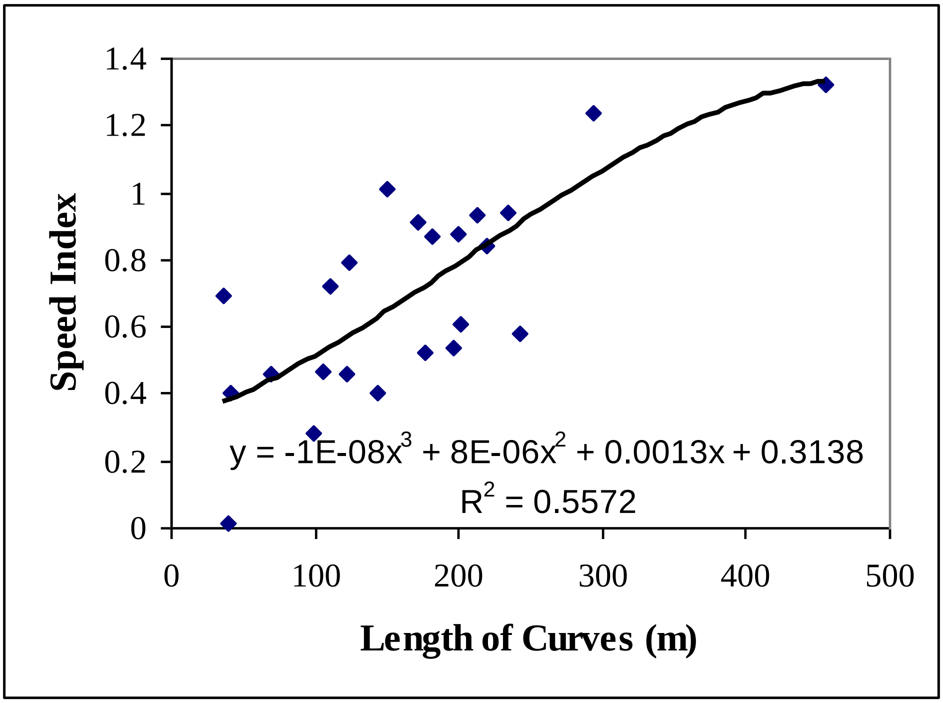

Figure (6): Consistency of horizontal curves according to curvature length

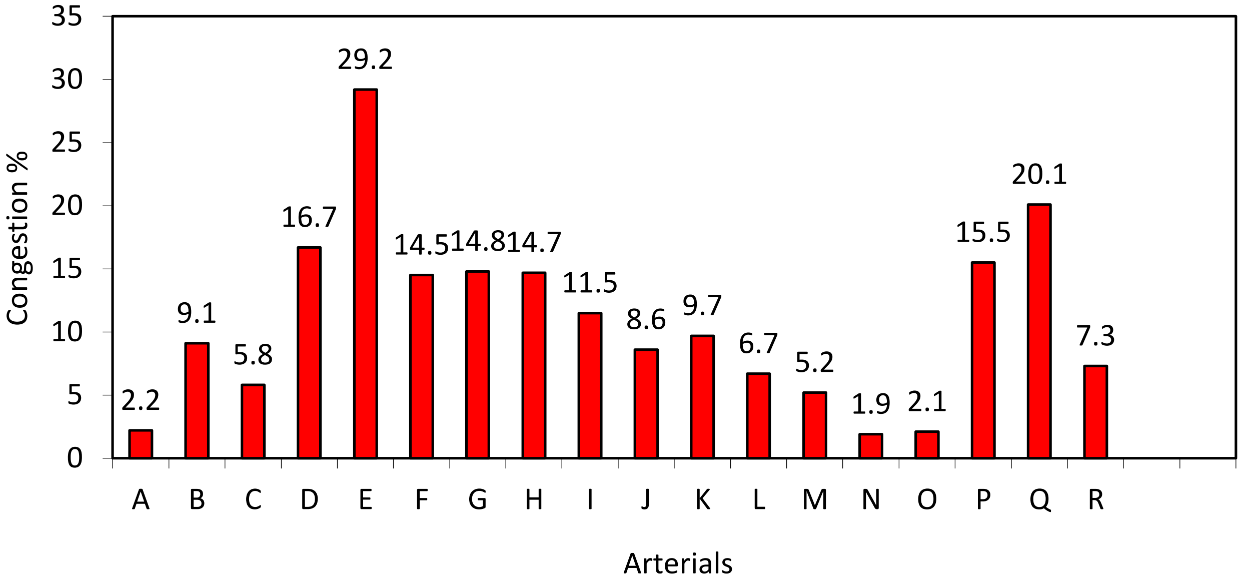

Figure (7): Congestion quantification at peak period

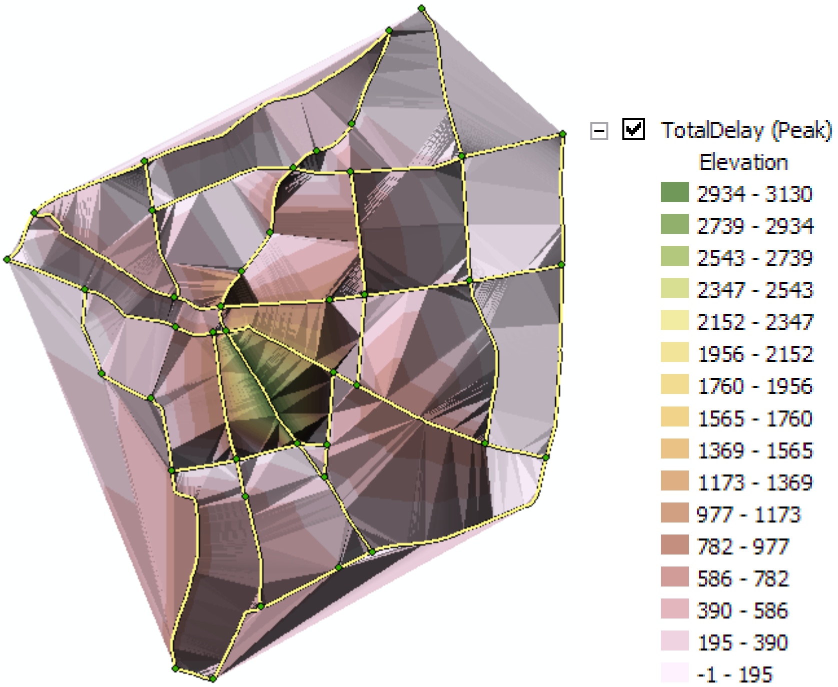

Figure (8): Spatial map of total delay during peak period

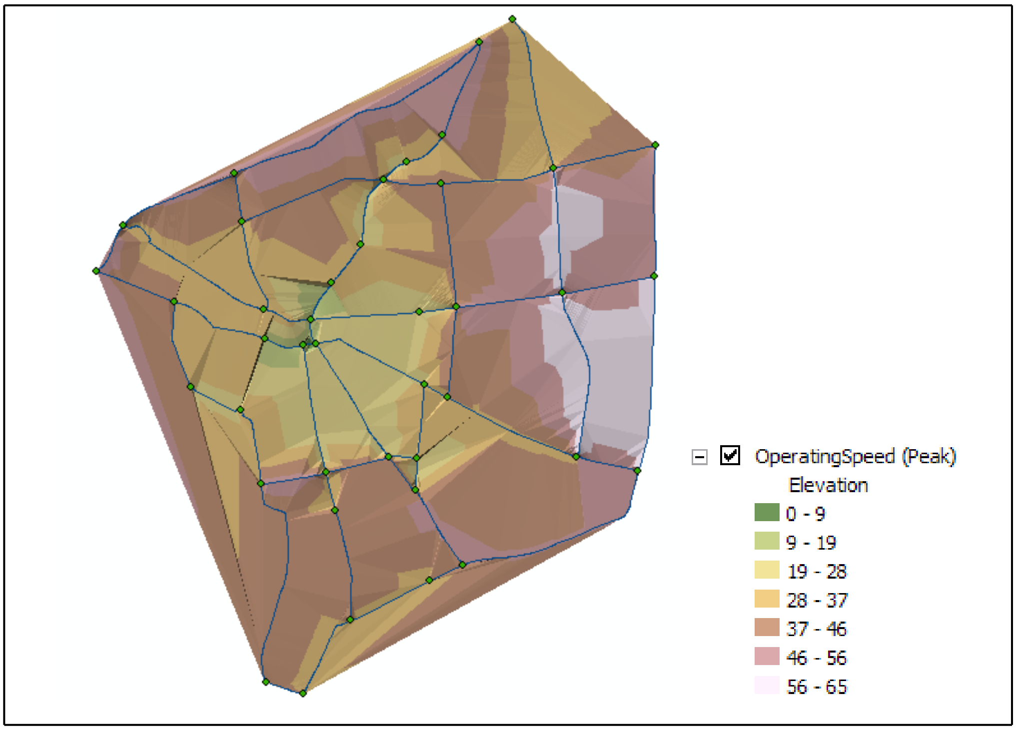

Figure 9: Spatial map of operating speed during peak period

Spatial Analysis of Travel Time Variables

Spatial analysis was conducted based on operating speed and total delay of segments. Figure 8 shows the spatial map of total delay for segments during peak period. Another spatial analysis was conducted according to operating speed during peak period. Figure 9 shows the spatial map of operating speed for segments during peak period. Spatial maps of segments based on travel time components were important to make an approximate estimation for operating speed, and associated delays for other segments were not included in the study segments of this research.

CONCLUSIONS AND RECOMMENDATIONS

The application of GPS and GIS technologies in data collection gives detailed study of traffic conditions and provides a database for all the road segments in the study area. The GPS technology makes the task of database building more manageable and cost effective. This research is a preliminary study that aims to investigate how urban roadway environments affect journey's travel time and how to evaluate the urban arterials' performance. Therefore, planners and operators can use this knowledge to design more consistent roads and reduce congestion. Thus, consistency provides a new performance measure of urban streets that can be used to ease utilizing GPS data incorporated with GIS capability.

This research work found that divided arterials with ring road function, more length, more than one lane and located at residential areas were more consistent with their posted speed limits than other arterials. Moreover, congestion can be quantified using a new scheme proposed in this research work utilizing spatial analysis of GIS and second-by-second GPS data. However, it is important to mention that further studies are needed to expand the usage of consistency as a performance measure of roadways in urban areas.

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). (2004). "A policy on geometric design of highways and streets, and roadside design guide". Washington, D.C.

Fitzpatrick, K., Carlson, P., Brewer, M.A., and Wooldbridge, M.D. (2003). "Design speed, operating speed and posted speed practices". Presented at the 82nd TRB Annual Meeting. Washington, D.C.

Garber, N.J., and Gadiraju, R. (1989). "Factors affecting speed variance and its influence on accidents". In: Transportation Research Record 1213, TRB, National Research Council, Washington, D.C.

Krammes, A., Brackett, Q., Shaffer, A., Ottesen, L., Anderson, B., Fink, L., Collins, M., Pendleton, J., and Messer, J. (1994). "Horizontal alignment design consistency for rural two-lane highways". Research Report FHWA-RD-94-034, FHWA, U. S. Department of Transportation.

Laird, D. (1996). "Emerging issues in the use of GPS for travel time data collection". National Traffic Data Acquisition Conference, Albuquerque, NM, 6-9 May, 1, 117-123.

Lomax, T., Turner, S., Shunk, G., Levinson, H. S., Pratt, R. H., Bay, P. N., and Douglas, G.B. (1997). "Quantifying congestion: volume 1, final report". National Cooperative Highway Research Program (NCHRP), Report 398. Washington, D.C.: National Academy Press.

Martin, P.T. (2002). "Real time measures of effectiveness". University of Utah.

McLean, J.R. (1979). "An alternative to the design speed concept for low speed alignment design". Transportation Research Record 702, TRB, National Research Council, Washington, D.C.

Obaidat, M.T., Al-Jayyousi, O., and Al-Masaeid, H.R. (1997). "A new methodology for evaluating geometric performance of highways". Highway Research Bulletin (IRC), Indian Road Congress, Highway Research Board, 57, 1-20.

Quiroga, C. A., and Bullock, D. (1998). "Measuring delay at signalized intersections using GPS". Draft paper submitted to the ASCE Journal of Transportation Engineering.

Quiroga, C.A. (2000). "Performance measures and data requirements for congestion management systems". Transportation Research Record, National Research Council, Washington, D.C., 287-306.