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Satellite Imagery Applications of Urban Road Inventory, Traffic Flow Attributes, and Road Capacity Assessment

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***Abstract*— Road inventory and traffic volume demand maps are the most important elements of a working traffic management system. In some countries these up-to-date road inventory data are not available and 24-hour traffic counts are not frequently collected due to lack of funds or difficult to access remote places. The authors discuss a geospatial methodology using 0.6m high resolution satellite imagery that was successfully implemented for creating road network planimetrics for road inventory, traffic flow attributes, and traffic volume demand maps. The capacity analysis results show that the analyzed urban road sections were mostly at level-of-service C, D, or E. The traffic demand volume data can be used to calculate congestion costs and recommend traffic management priorities.**

***Keywords*— Capacity, geospatial analysis, inventory, road, satellite imagery, traffic flow, volume.**

I. Introduction

A. Traffic Mobility, Congestion, Safety, and Capacity

The efficient public mobility, emergency management during disasters, commuting to workplace, delivery of goods and services, access to consumer services, creation of new businesses, and job growth, all depend on good and safe transportation infrastructure assets [1]. The World report on road traffic injury prevention [2] underscores the concern that unsafe road traffic systems are seriously harming global public health and development. Worldwide, an estimated 1.17 million people are killed in road crashes each year and as many as 50 million are injured. The annual road fatalities decreased in the U.S. from over 43,000 in early 2000's to below 40,000 within the last five years due to safety related investment in road infrastructure and traffic management. In developing countries, rapid urbanization and traffic congestion due to road network capacity constraints has resulted in higher fatalities [1]. In the U.S. less than 0.3 % road vehicles are motor cycles. On the other hand, in many developing countries in South and South East Asia motor cycles constitute a significant portion of the traffic mix (about 25 % in Pakistan and 30 % in Malaysia). Pakistan has a high fatality rate of 19 deaths per 10,000 vehicles [1]. The majority of road crash victims (injuries and fatalities) in developing countries are not the motorized vehicle occupants, but motorcyclists, bicyclists, pedestrians, and non-motorized vehicles occupants.

The deficiency of road infrastructure assets and traffic demand exceeding road capacity pose significant challenges to traffic safety and traffic flow management in many cities of Pakistan and other developing countries. Traffic demand volume data is generally not update or missing for long periods due to insufficient funds needed for traditional labor intensive methods of on-site traffic data collection.

B. Objective

The primary objective of this research was to perform geospatial analysis of spaceborne satellite imagery for creating road and landuse maps, estimating traffic density & flow attributes, & analyzing capacity & level-of-service.

This study was a part of a joint research project of the University of Mississippi and NED University of Engineering and Technology for assessing and improving urban traffic flow management and air quality by implementing intelligent transportation system (ITS) traffic video surveillance technologies. This was the National Academies/USAID (U.S. Agency for International Development) project [3] titled "Development of an ITS-Based Traffic Management Model for Metropolitan Areas of Pakistan with Karachi as a Pilot Study."

This paper presents a case study of an industrial site area in the port city of Karachi in Pakistan [4] where satellite imagery was used to: create planimetric inventory of area roads, landuse map, extract traffic flow attributes of selected sections of an arterial road, calculate daily volume distribution, and evaluate level of service of road sections.

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C. Traffic Problems in the Megacity of Karachi

Roads represent the dominant mode of inland mobility and traffic in Pakistan and carry 91% of passenger traffic and 96% of freight traffic. Over the past decade, Pakistan has worked intensively to build and modernize motorways and national highways as part of the country's overall economic development efforts [3]. However, traffic-related fatalities are alarmingly high, and about 41% of all crashes are fatal, a figure that is significantly higher than in most other countries. Frequent congestion and transportation choke points in most urban and metropolitan areas are adversely affecting travel time, business operating costs, and air quality. Increased air pollution (particulate matter particularly) is affecting public health, especially in terms of respiratory diseases and mortality rates.

Karachi is the largest metropolitan city of Pakistan and one of the megacities in the world. This megacity is the financial and business hub of Pakistan and being the only large port city, serves Pakistan and the landlocked Afghanistan in the central Asian region. The city had a population of over 14 million in 2007. Karachi has seen a 35-fold increase in its population and an almost 16-fold increase in its spatial expansion since the creation of Pakistan in 1947. Moreover, estimates are that by the year 2015, the city may reach a population of 19.2 million at an annual growth rate of 5% [5]. Karachi with about 10% of the country's population, has suffered the most from this growth in urban population and inadequate supply of road infrastructure. Figure 1 shows typical views of transit bus overloading and extremely congested roads with mixed traffic commonly observed in Karachi during long rush hours.

FIGURE I
TRAFFIC CONGESTION SCENES IN THE MEGACITY OF KARACHI, 2007-2008

The total number of registered vehicles in Karachi increased to 1.8 million in 2007 at 10.18% growth rate since 2002, which was almost twice compared to the population growth rate. Cars and taxis make almost half of the traffic on the roads of Karachi. Second largest group of vehicles is motorcycles, which makes 40% of the traffic mix. The remaining 10% of the traffic is composed of other vehicle types including buses, transit vehicles, motor rickshaws, and loading pickups. It should be noted that the mass transport buses constitute only 1.3% of the total traffic while serving most commuters.

Pedestrian traffic is another significant contributor to annual traffic fatalities on the roads of Karachi. At the outset of this study in 2007 frequent gridlocks and traffic jams were observed on the road network of Karachi during long rush hours, which result in excessive user delays and more vehicle emissions causing continuous degradation of air quality.

There was no readily available road-specific traffic volume demand database or geographical information system (GIS) maps for the entire road network in Karachi [3]. Therefore, the primary motivation of this research was to implement high resolution satellite imagery and geospatial analysis methodologies to analyze characteristics of traffic flow, create traffic volume demand data, and develop a GIS-based road inventory map for Karachi for a better traffic management system.

II. SPACEBORNE REMOTE SENSING AND GEOSPATIAL TECHNOLOGIES FOR ROAD ASSET MANAGEMENT

Efficient management of infrastructure assets requires a database of inventory and condition data [6]. Infrastructure monitoring data has been traditionally acquired using ground-based or airborne methods. Remote sensing technologies have been widely used for geological, military, environmental, urban planning, hydrological, and transportation planning. Remote sensing and geospatial technologies are particularly useful to accomplish the database of both geographic data and non-geographic attributes [7].

In recent years, worldwide coverage of high resolution satellite imagery has been available on affordable costs for planimetric extraction of road inventory and landuse maps for applications in infrastructure asset management and traffic management [8]. The use of non-intrusive 1-m and submeter resolution satellite imagery has been proved very cost-effective, less labor intensive, and less time consuming. In addition, geospatial analysis of the archived satellite imagery can provide a unique opportunity to evaluate temporal changes in landuse patterns, traffic demand trends, disaster impacts, and biodiversity and environmental sustainability.

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A. Application of Satellite Imagery for Road Network Inventory and Traffic Volume Maps

High resolution satellite imagery such as 1-m Ikonos or 0.6-m QuickBird2 have been used for the development of accurate and precise landuse and road inventory maps in the Karachi transportation management project [3]-[5]. Traffic data extraction from satellite imagery is another important application of remote sensing technologies in transportation planning projects. The traffic data obtained from the satellite imagery can be compared with the ground-based samples to check the accuracy of the data obtained from the satellite imagery. Figure 2 shows the ground resolution of 15-m Landsat7 imagery used for regional level landuse studies and 0.6-m QuickBird2 imagery that can be used to map roads and detect road vehicles.

FIGURE 2
LANDSAT7 (LEFT) AND 0.6-m QUICKBIRD2 (RIGHT) SATELLITE IMAGERY SCENES FOR KARACHI PORT AREA

B. Geospatial Methodology of Imagery-based Traffic Flow Attributes

A scene of georeferenced satellite imagery is a snapshot of road traffic density for the hour when the imagery was collected. The 0.6-m pan-sharpened QuickBird2 imagery, used for extraction of road planimetrics and traffic flow attribute data, was acquired on Tuesday, Mach 07, 2007, at 11:36:59 Pakistan Standard Time (PST). The multispectral imagery had four spectral image bands (red, green, blue, and near infrared or NIR). In this study, traffic density was extracted by counting number of vehicles in the sample length of a selected road in a GIS map window zoom view of the imagery. This provides traffic density data that can be further processed to estimate traffic flow attributes and average daily traffic volume. Reasonable estimates of rush hour traffic flow and 24-hour traffic volume distribution were available for this area [4]. Using a linear vehicle speed-density model and knowledge of typical 24-hour volume distribution, average daily traffic volume for the sample road section was calculated from traffic density.

The geospatial methodology adapted to extract the traffic volumes for the selected road network comprised of the following steps:

1. Measuring the length, width, and number of lanes of each section using geospatial analysis tools in geospatial software, GeoMedia Pro;
2. Counting the number of vehicles in each lane from the selected section of the imagery in geospatial software;
3. Calculating traffic density and space headway for each road section;
4. Estimating space-mean speed for each section based on the space headway;
5. Calculating imagery-hour traffic flows using traffic density and space-mean speeds for each section; and
6. Calculating daily traffic volumes for each section using the hourly traffic volume factor for the imagery-hour based on estimates of typical hourly traffic volume factors for 24 hours.

The above methodology was used for the extraction of traffic data on selected road sections from 0.6-m multispectral QuickBird2 imagery of Karachi. Other geospatial methodologies [10]-[11] rely on supervised pixel classification of road and vehicles. Their accuracy is affected by several factors such as pixel reflection variability due to time of day of the imagery acquisition, seasonal variations, vehicle color, and materials used for vehicle manufacturing. The proposed methodology is a practical approach where only vehicles are counted manually using zoomed views of the imagery and other geometrical features are extracted easily from GIS planimetric functions. This traffic data along with the geometry of the road network, extracted from satellite imagery, can be used for traffic flow microsimulation and capacity analysis of the road network. Using satellite imagery scenes, the traffic attributes and road geometry are also georeferenced for producing spatial maps of daily traffic volume and other flow attributes. This is difficult to accomplish using traffic video based vehicle count approach.

Other outputs from the imagery-based traffic flow analysis include evaluation of existing traffic control strategies, congestion and delays, and level-of-service (LOS) for selected road sections. The capacities and LOS values for the selected road sections were calculated using the AASHTO method described in the 2000 Highway Capacity Manual (HCM) standards [12].

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III. Selected Road Network Section for Imagery Based Inventory and Traffic Volume Demand

The selected road sections, in a large industrial zone on SITE Avenue and Hakim Ibn-e-Sina Road, are a part of the signal-free corridor-I in Karachi. This road connects Karachi seaport and SITE industrial town with the E.C.O Highway, Karachi's Quid-e-Azam International Airport, and National Highway. The traffic originating from the Karachi Port uses this road to access the National Highway. Therefore, this corridor represents the most important link in the road infrastructure of the national supply chain from Karachi to northern parts of the country and beyond across the border with Afghanistan.

A. *Imagery-based Traffic Flow Attributes for Site Avenue*

The GIS map of the selected road sections of SITE Avenue is shown in Figure 3. The selected road (SITE Avenue and Hakim Ibn-e-Sina Road) was divided into seven sections named from A to G and analyzed in each direction, as shown in Figure 3 (right). There are three intersections on the selected road: two signalized intersections, namely the Ghani Intersection, and the Habib Bank Intersection and the Siemens Roundabout. The Ghani Intersection at the intersection of Section-C and Section-D, is a four-leg intersection of SITE Avenue and Central Avenue. The Habib Bank Intersection, located at the intersection of Section-E and Section-F, is shown in Figure 3 (left). It is a four-leg intersection of SITE Avenue, Hakim Ibn-e-Sina Road, and Manghopir Road. Siemens Roundabout is a Y-intersection of SITE Avenue and Siemens Road.

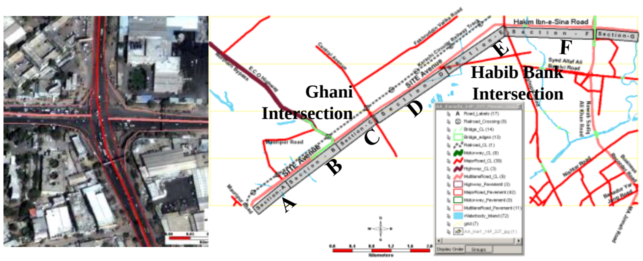

FIGURE 3
IMAGERY OF HABIB BANK INTERSECTION (LEFT); SELECTION ROAD NETWORK AND SECTIONS FOR THE EXTRACTION OF TRAFFIC DATA (RIGHT)

The numbers of vehicles were counted manually from the imagery, and the length of the segment was calculated using the Geometry Analysis tool of the GIS program, GeoMediaPro6.0. These data were used to analyze traffic flow attributes on the selected road sections. While counting the number of vehicles, vehicles were not classified in this study. This was done in a follow up study. In this paper, traffic composition was estimated using the number of vehicles counted from the imagery and the typical traffic composition of 2007 registered vehicle data for Karachi. The traffic density was calculated using the following equation:

$$k = \frac{N}{L} \times 1000 \quad (1)$$

Where, k is traffic density (veh/km); N is number of vehicles counted for the section from the imagery (veh); and L is length of the road section (m).

Space headway is defined as distance between any given points between two consecutive vehicles. The following equation describes the relationship between traffic density and average space headway:

$$h = \frac{1}{k} \times 1000 \quad (2)$$

Where, h is average space headway (m) and k is traffic density (veh/km). The average space-mean speed for vehicles is required to calculate hourly traffic flows and daily volumes. The space-mean speed for a section of the selected road is estimated based on average space headway. The speed limit for the selected road was considered as 50km/h (31.5 mi/h). Table 1 shows the criteria used for estimating space-mean speed from average space headway.

TABLE II
SPACE-MEAN SPEED CALCULATIONS BASED ON AVERAGE SPACE HEADWAY

No.	Density, k (veh/h/ln)	Spaceheadway, h=1x1000/k (m/veh/ln)	Speed, u, (km/hr)	Volume, v = k x u (veh/h/ln)
1	<17	>60	50	<850
2	17-25	40-60	40	680-1000
3	25-50	20-40	30	750-1500
4	50-100	10-20	20	1000-2000
5	>100	<10	10	>1000

Imagery-hour traffic volumes were calculated using the traffic densities extracted from the imagery and the estimated space-mean speed (Eq. 3):

$$q = k \times u \quad (3)$$

Where, q is traffic flow (veh/hr); k is traffic density (veh/km); and u is space-mean speed (km/hr).

The daily traffic volume for each section of the selected road was calculated based on the imagery-hour traffic flow. The daily traffic volume can be calculated if proportion of the daily traffic flowing during the imagery-hour is known. Hourly factors were estimated to find the proportion of the daily traffic volume in each hour of the day. These typical hourly factors were used for all the sections in the network. These hourly traffic volumes are based on ground-truth observations of roads in SITE and port areas of Karachi [9]. Figure 4 shows the plot for estimated hourly traffic factors.

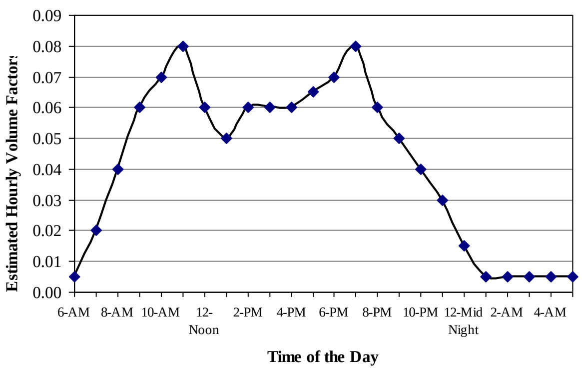

FIGURE 4
ESTIMATED HOURLY TRAFFIC VOLUME FACTORS FOR 24 HOURS

The peak hours were estimated to be between 11:00-12:00 AM PST in the morning and 7:00-8:00 PM PST in the evening. It was estimated that 8% of the daily traffic is flowing during the imagery-hour. Traffic flow for each hour of the day was also calculated using the hourly traffic volume factors. Average annual daily traffic volume (AADT) can be calculated by dividing the imagery-hour volume by the proportion of traffic during the study hour (hourly volume factor), as shown in the following equation:

$$V = \frac{q}{H_f} \tag{4}$$

Where, V is estimated AADT daily traffic volume; q is Imagery hour traffic flow (vph); and H_f is estimated hourly factor. Exhibit 16-2 in HCM [12] was used to determine appropriate LOS from delays estimated for each lane group and aggregated for each approach. The calculated 2007 traffic volumes, delay, and LOS follow for the four legs of Habib Bank intersection:

Section	Lane	Peak vph	LOS	AADT
• Site Ave, E-1	2	1,850	D	23,125
• Ibn Sina Rd, F-2	3	1,500	D	18,750
• Manghopir Rd, N-S	2	1,890	D	23,625
• Manghopir Rd, S-N	2	1,560	D	19,500

B. *Imagery-based Traffic Flow Attributes for Siemens Roundabout*

Siemens roundabout is a three-legged roundabout intersection of the Siemens road and the SITE Avenue. The 0.6-m imagery and planimetrics of Siemens roundabout is shown in Figure 5. The number of vehicles in the circling lane calculated using the assumed turning volume proportion was seven vehicles. Total eight vehicles were counted from the imagery circulating around the roundabout, which is close to the number of vehicles calculated. Therefore, it was concluded that assumption for the turning volumes for the intersection was reasonably correct.

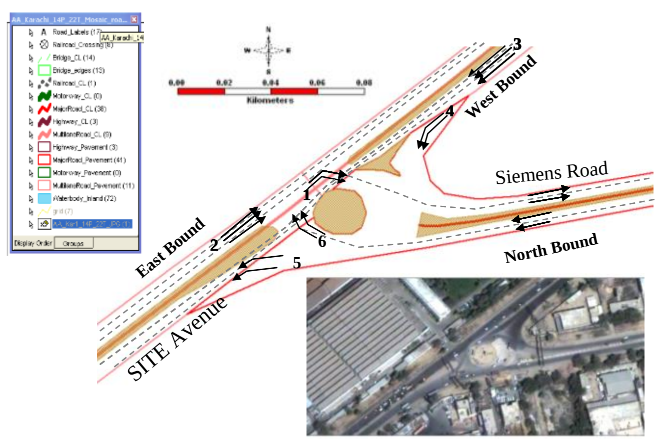

FIGURE 5
IMAGERY, PLANIMETRICS, AND TRAFFIC DIRECTIONS AT SIEMENS ROUNDABOUT

The calculated 2007 traffic volumes, delay, and LOS follow for the Siemens roundabout junction:

Section	Lane	Peak vph	LOS	AADT
• Site Ave, D-1	3	1,550	C	19,375
• Site Ave, D-2	2	1,450	A	18,125
• Siemens Rd, S-N	2	900	B	11,250

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The 2007 LOS results for the study road sections were verified by the imagery-based traffic density results. Based on AASHTO definition, at the LOS C most experienced drivers are comfortable, roads remain safely below but efficiently close to capacity, and posted speed is maintained while at the LOS D the drivers are forced to reduce the speed and vehicles cannot move freely [12].

Capacity was calculated using the following Eq.

$$c_a = \frac{v_c e^{-v_c t_c /3600}}{1 - e^{-v_c t_f /3600}} \quad (4)$$

Where, C_a = approach capacity;
v_c = conflicting circulating traffic (veh/h);
t_c = critical gap (s), 2.6 to 4.1 sec; and
t_f = follow-up time (s), 3.1 to 4.6 sec.

IV. Results and Discussions

The imagery-based peak-hour flow and AADT daily traffic volume data were used for capacity and LOS analysis of seven selected road sections (total 14 approaches), two signalized intersections, and one roundabout in the selected roads using the 2000 HCM method [12]. Table 2 shows the results for two straight sections (6 approaches) and three junctions. Daily traffic volumes were projected for future 10 years at an annual growth rate of 5% as given in Table 2. Comparison of 2007 estimated LOS for these sections operating at C and D (Table 2) with the 2017 capacity analysis showed that three movements from straight sections were estimated at LOS C while one movement at LOS C and one at LOS E in 2017.

Considering projected traffic volumes in 2017 at Ghani and Habib Bank intersections four movements have estimated LOS of F, two movements have estimated LOS E, and two movements have estimated LOS D for 2017. This indicates that these roads sections should be improved for traffic flow before LOS deteriorates further in 2017. Overall results for the three road junctions follow:

- *Ghani Intersection*: It was estimated that this was at LOS E in 2007, which will be operated at LOS F for the projected traffic volumes in 2017. Therefore, this intersection should be considered for improvement.
- *Habib Bank Intersection*: It was verified from the imagery-based traffic density that this intersection was being operated at LOS D in 2007, which will deteriorate to D and E in 2017.
- *Siemens Roundabout*: The northbound approach was estimated at LOS B, eastbound approach was at LOS A, and the westbound approach of the roundabout was at LOS C. This junction operated satisfactorily.

TABLE 2
SUMMARY OF LOS FOR THE STUDY ROAD SECTIONS FOR 2007 AND 2017

Road Sections	No. of Lanes	2007 AADT	2007 LOS	2017 AADT	2017 LOS
SITE Ave E-1 (Th)	3	23,125	C	37,663	C
SITE Ave E-2 (Th)	3	18,125	C	29,525	C
Hakim Ibn-e-Sina Road F-1 (Th)	3	30,000	C	48,863	D
Hakim Ibn-e-Sina Road F-2 (Th)	3	18,750	C	30,538	C
Hakim Ibn-e-Sina Road G-1 (Th)	3	21,250	D	34,613	E
Hakim Ibn-e-Sina Road G-2 (Th)	3	14,375	D	23,413	D
SITE Ave C-1 (Ghani Sig intersec)	3	30,375	E	49,475	F
SITE Av D-2 (Ghani Sig intersec)	3	20,625	E	33,600	F
Central Ave N (Ghani Sig. intersection)	2	22,125	E	36,038	F
Central Ave S (Ghani Sig. intersection)	2	27,038	E	44,038	F
SITE Ave E-1 (Habib Bank Intersec)	3	23,125	D	37,663	E
Hakim Ibn-e-Sina Road F-2 (Habib Bank Intersec)	3	18,750	D	30,538	D
Manghopir Rd N (Habib Bank Intersec)	2	23,625	D	38,488	E
Manghopir Rd S (Habib Bank Intersec)	2	19,500	D	31,763	D
SITE Ave D-1 W (Siemens roundabout)	3	19,375	C		
SITE Ave D-2 E (Siemens roundabout)	2	18,125	A		
Siemens Road N (Siemens roundabout)	2	11,250	B		

*LOS Criteria [12]: A (Delay ≤ 10); B (Delay > 10-20); C (Delay > 20-35); D (Delay > 35-55); E (Delay > 55-80); F (Delay > 80)

The number of vehicles in circling lanes at Siemens Roundabout, calculated using estimated traffic volumes, compared reasonably well with the number of vehicles counted from the circling lanes on imagery snapshot.

The study results show that imagery based traffic density data extraction is a viable methodology and less costly for areas with non-existent traffic data measurements or where funding constraints prohibit expensive manual counts or automated traffic counting equipment. These results can be used to estimate past traffic volumes, plan for future ITS video surveillance locations, and prioritize road locations for implementing appropriate traffic management strategies. The traffic attributes can be used to calculate congestion costs and related attributes during peak hours including: travel time delay, fuel wasted, and emissions.

The study demonstrates that the proposed geospatial methodology is an efficient approach, compared to significantly more costly and time consuming conventional methods of field surveying and field traffic data collection. A follow-up study used even freely available web-based satellite imagery to extract traffic attributes.

V. Conclusions

This research provides an innovative use of high resolution satellite imagery data and geospatial analysis to estimate daily traffic volume demand data. Key findings are:

- The study results show that out of all sections of SITE Avenue, Ghani Intersection was being operated at LOS E that will deteriorate to LOS F for the 2017 projected traffic volume. This road section should be given the top priority for improvement.
- The study results prove that imagery-based planimetric of road network and traffic density and volume data extraction are viable and less costly for areas with non-existent GIS maps and inadequate traffic data measurements.
- The imagery-based approach of road inventory and traffic data collection saves funds and time, compared to significantly more costly and time consuming conventional methods of field surveying to create GIS maps and field traffic data collection.

These results can be used to estimate past traffic volumes, congestion attributes during peak hours, plan for future ITS video surveillance locations, and prioritize road locations for implementing appropriate traffic management strategies.

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