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Research Article

DETERMINATION OF HIGHWAY BOTTLENECKS BY USING INTELLIGENT TRANSPORTATION SYSTEMS AND GEOGRAPHIC INFORMATION SYSTEMS

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ABSTRACT

An occurrence of congestion at a highway segment, also named bottleneck, is one of the major problems of traffic. As a result of the bottlenecks, vehicle speeds are transparently decreased and its effects continue on the traffic flow by acting upstream or downstream as an interface for a while. Thus, negative effects are observed over the capacity of the highway segment where the bottleneck occurs until traffic flow returns to normal conditions again. Therefore, traffic engineers aim to avoid this major problem in design and operation of highways.
Intelligent Transportation System (ITS) is an advanced application that is used to utilize existing infrastructure more effectively instead of building new infrastructures. Today, ITS has been one of the trend study fields thanks to the development of technology and through the spread of smart cities. Automatic Vehicle Location (AVL), a powerful tool to manage fleets such as service vehicles, emergency vehicles, or public transit vehicles, is a GPS-based technology within the context of the ITS. So, agencies and organizations can follow vehicles of their fleets by utilizing satellites.
In this study, an AVL dataset, integrated into public transportation systems, and Geographic Information Systems (GIS) are used to detect bottlenecks in a highway segment in Istanbul. The results showed that if the locations of bus stops and traffic signals are known, the segments, where bottlenecks occur and congestion increases, may be determined by using AVL data.
Keywords: Automatic vehicle location, bottleneck detection, geographic information system, intelligent transportation system, traffic congestion.

1. INTRODUCTION

Bottleneck is a well-known phenomenon that refers to sections in which average speed drops suddenly on a highway segment during the usual traffic flow. The occurrence of this phenomenon may be caused by the geometric design of the highway, extreme volume increase during peak hours, heavy vehicle effect, traffic signals, an incident or abnormal driver behavior in the highway section. As a result of sudden changes at a bottleneck segment, an interface between the free flow and the congested traffic occurs and this interface moves upstream or downstream and long

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queues occur. Due to the negative impacts on highway capacity, bottlenecks have an important place in theoretical and applied researches [1, 2].

On a highway segment, free-flow conditions are applicable up to the capacity of the bottleneck (CoB). So, vehicles move independently from each other and there is no restriction on vehicle movements, and congestion or queue are not observed on the highway up to the CoB. However, if traffic demand exceeds the CoB, forced flow conditions are applicable; naturally, traffic congestion and queue occur at the segment. In the United States, the Federal Highway Administration (FHWA) reported that 40% of traffic congestion is caused by bottlenecks. Also, bottlenecks may cause traffic crashes [3]. In addition to safety issues, incidents also cause congestion. Therefore, traffic engineers and decision-makers should consider to prevent bottleneck occurrence while designing and operating highways [5]. One of the methods used to operate traffic is to use Intelligent Transportation Systems (ITS).

ITS, as an interdisciplinary study field with the integration of computer, telecommunication and electric-electronic sciences, has many functions such as increasing the performance of transportation systems, ensuring travel safety and offering alternative ways to users using the existing infrastructure. Besides, thanks to ITS, a significant amount of data about transportation systems can be obtained and stored. Today, it is possible to provide transportation optimization and coordination with the data obtained by ITS, which has become more popular with the concept of smart city. Data such as Radio Frequency Identification (RFID), Remote Traffic Microwave Sensor (RTMS), Loop Detector, Smart Card and Automatic Vehicle Location (AVL) can be given as an example collected by ITS devices [6, 7].

In the literature, AVL data are used to determine bus bunching [4, 5], to improve the scheduling, to evaluate service quality and operation of vehicles [8-13], to forecast arrival and departure time of vehicles [14, 15], to improve priority models [16], to evaluate of traffic conditions [17], in the evaluation of travel time and dwell time [18-21], to detect movable asset anomalies [22] and in many different studies. In this study, a methodology including Automatic Vehicle Location (AVL) data, which is a component of ITS, and Geographic Information Systems (GIS) software is presented to identify bottlenecks on a highway corridor. AVL data integrated tire-wheeled public transportation system was provided from Istanbul Metropolitan Municipality (IBB).

2. MATERIAL AND METHODOLOGY

2.1. Route

In this study, the section with a length of 12.7 kilometers on coast road between Eminönü and Zeytinburnu (Kennedy Street), shown in Figure 1, was chosen as the study area. This road has a significant traffic volume on the east-west direction during the day. Also, congestion problems occur frequently along the route. In this direction, there are traffic congestions, especially in the evening because of rush-hour after work. Therefore, a methodology to determine the segments where congestion is experienced, namely bottleneck, is presented by working on this route. There are 18 bus stops and 11 signals in one direction (Eminönü to Zeytinburnu) along the route.

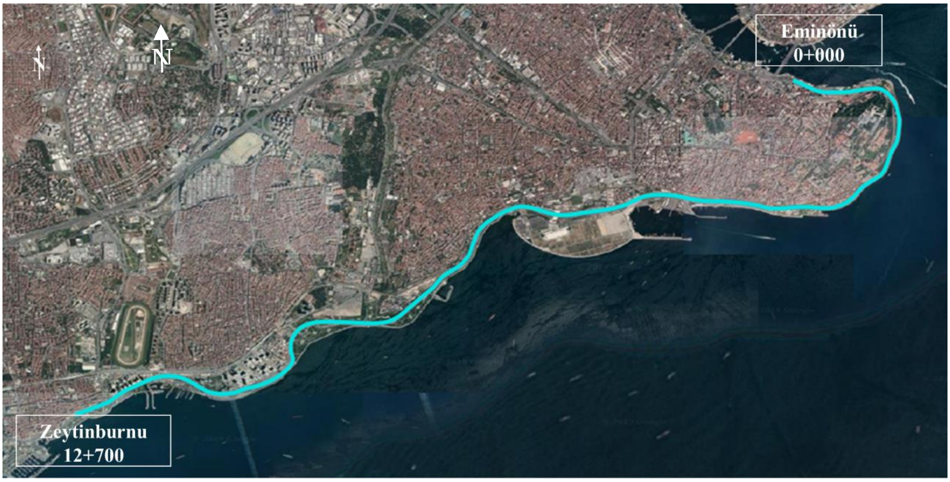

Figure 1. Selected route from E minönü to Zeytinburnu

2.2. Data

AVL data, a component of ITS, was provided by IBB. Data records contain bus location ID, bus gate number, reading time, longitude, latitude, speed, distance, recording time and bus line. AVL raw data recorded approximately at 15 seconds intervals were obtained. The data of the BN2 bus line recorded on 18/10/2016 were used in the study and Table 1 shows a sample of it.

On the date of 18/10/2016, 58 of the vehicles operating on the BN2 line were observed moving from Eminönü to Zeytinburnu and data of these vehicles were used. The route of the BN2 bus line was planned as a round trip between Eminönü and Küçükçekmece along the coastal road depicted in Figure 2.a [23]. However, when the raw data is examined, it is seen that a large amount of location was read out of the normal route (Figure 2.b). This is due to the fact that when the vehicle operates for a different line, the AVL devices on the vehicles are not updated by the respective personnel (usually driver). For this reason, for an accurate evaluation, the location data which are out of route were cleaned first, and preliminary preparation was made (Figure 2.c).

Table 1. Sample AVL data

BUS LOCATION ID	BUS GATE NUMBER	READING TIME	LONGITUDE	LATITUDE	SPEED	DISTANCE	REC. TIME	BUS LINE
744291687	M4732	18.10.2016 16:36:53	28.88396000	40.97783000	50	1261	18.10.2016 16:36:53	BN2
744431804	M4732	18.10.2016 16:37:08	28.88591380	40.97850420	27	1263	18.10.2016 16:37:08	BN2
744374667	M4732	18.10.2016 16:37:24	28.88634300	40.97874000	23	1263	18.10.2016 16:37:24	BN2
744520295	M4732	18.10.2016 16:37:39	28.88784410	40.97977000	51	1265	18.10.2016 16:37:39	BN2
744457769	M4732	18.10.2016 16:37:54	28.89039800	40.98092000	61	1267	18.10.2016 16:37:54	BN2
744333142	M4732	18.10.2016 16:38:10	28.89162000	40.98141000	0	1268	18.10.2016 16:38:10	BN2
744405524	M4732	18.10.2016 16:38:26	28.89162000	40.98141000	0	1268	18.10.2016 16:38:26	BN2
744384942	M4732	18.10.2016 16:38:42	28.89297290	40.98170000	44	1270	18.10.2016 16:38:42	BN2
744322524	M4732	18.10.2016 16:38:58	28.89490320	40.98169330	26	1271	18.10.2016 16:38:58	BN2
744514926	M4732	18.10.2016 16:39:14	28.89649200	40.98100660	33	1273	18.10.2016 16:39:14	BN2
744390274	M4732	18.10.2016 16:39:29	28.89831540	40.97996520	42	1275	18.10.2016 16:39:29	BN2
736616915	A-1643	18.10.2016 16:39:45	28.88321000	40.97763440	64	709	18.10.2016 16:39:45	BN2
736583364	A-1643	18.10.2016 08:55:28	28.88561250	40.97841000	47	712	18.10.2016 08:55:28	BN2
736688471	A-1643	18.10.2016 08:55:44	28.88614850	40.97862240	38	712	18.10.2016 08:55:44	BN2
736592885	A-1643	18.10.2016 08:56:00	28.88664250	40.97900770	71	713	18.10.2016 08:56:00	BN2
736698039	A-1643	18.10.2016 08:56:15	28.88763000	40.97961000	70	714	18.10.2016 08:56:15	BN2

Figure 2. (a) Normal route and bus stop locations, (b) Raw data with abnormal positions and (c) Clean data of BN2 bus line on 18/10/2016

2.3.Methodology

In this study, methodology that shown in Figure 3 was applied to determine bottlenecks.

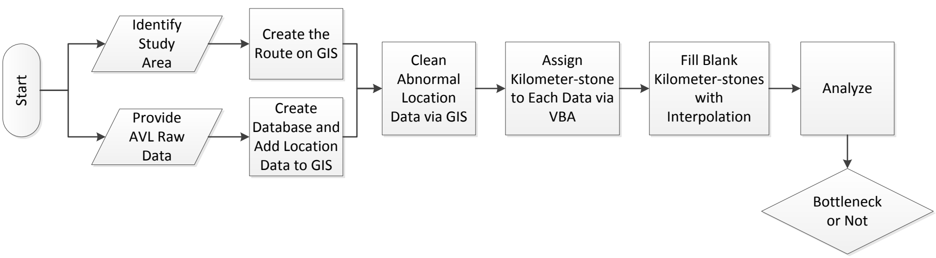

Figure 3. The methodology of the study

Firstly, a line that was 12700 meters long was drawn along the selected route between Eminönü and Zeytinburnu through QGIS, an open-source GIS software, after the study area was identified. Then, approximately 114,000 AVL raw data provided by IBB was transferred to GIS. It was seen that the vehicles traveled on many routes (see Figure 2.a and Figure 2.b) other than the normal route of the BN2 line. Therefore, these data that were out of the route had to be cleaned. GIS was used for this clean process and clean data was obtained as shown in Figure 2.c. Thus, the total number of data, including vehicles traveling in both directions, has decreased significantly, and roughly 12,000-row data has remained.

Then, an Excel Macro (EM) code was generated through Excel VBA (Visual Basic for Applications) to determine the direction of vehicles and which kilometer-stone the AVL data belonged to. For this process, the line was split into 10 meters long sub-segments. Thus, kilometer-stones were defined each 10 meters (1270 in total) along the route. After specifying the kilometers of each sub-segment, the latitudes and longitudes of the midpoints of these sub-segments were determined by GIS. Sample of kilometer-stones with coordinates are shown in Table 2.

Table 2. Sample of Coordinates for kilometer-stones

ID	Latitude	Longitude	Km
0	41.01731427868570	28.97435590907420	0+010
1	41.01727414730420	28.97446234449110	0+020
2	41.01723867988130	28.97455279505130	0+030
3	41.01718889935680	28.97467175685720	0+040
4	41.01714528034400	28.97477577266020	0+050
5	41.01710166124000	28.97487978832320	0+060
6	41.01705804204490	28.97498380384630	0+070
7	41.01701442275870	28.97508781922950	0+080
8	41.01697080338140	28.97519183447290	0+090
9	41.01692718391290	28.97529584957630	0+100

An aerial photo for a section of the route and its sub-segments that were prepared in GIS are shown in Figure 4. It is seen that the AVL data points are scattered around the route (Figure 4.a). In addition, the midpoints of the sub-segments with assigned locations (latitude and longitude) and kilometer-stones, an example of which is shown in Table 2, are shown in Figure 4.b.

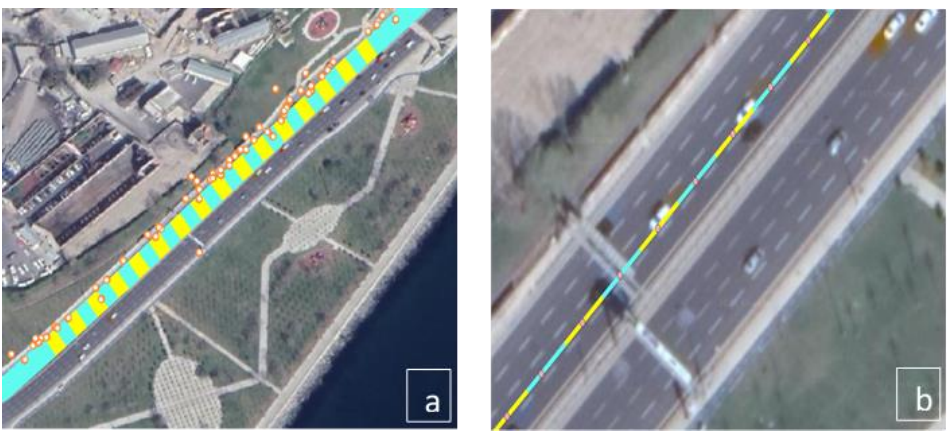

Figure 4. Aerial photo for a section of route with AVL data (a) and midpoints of the sub-segments (b)

In the study, analyzes were made just for one direction (Eminönü to Zeytinburnu), and so, the location data of the vehicles (a total of 5464 AVL data) moving by just this direction were used.

In order to assign kilometer-stones that shown in Table 2 to each AVL data, EM was run. Equation 1 was used to calculate the distance between two geographical coordinates. Here, according to the WGS84 system (*W*orld *G*eodetic *S*ystem that is a standard for use in cartography, geodesy, and satellite navigation including GPS), the value of *6378* is the diameter of the Earth in kilometers (to get the result in miles, should be used the value of 3959), *Lati* is the latitude of the point *i* and *Longi* is the longitude of the point *i* [24]. In this way, the distance between each AVL data and kilometer-stones was calculated with the help of this formula, and each data was assigned to the nearest sub-segment. A sample data with assigned kilometer-stones is shown in Table 3.

$$Distance = 6378 * arccos(cos(Lat\varphi) * cos(Lat\psi) * cos(Lng\psi - Lng\varphi) + sin(Lat\varphi) * sin(Lat\psi)) \quad (1)$$

Table 3. Sample AVL data with assigned kilometer-stones

Km	Date_Time	Latitude	Longitude	Speed	Distance	# of Gate
0+010	18.10.2016 08:51:50	41.0172577	28.9739971	33	422	A-1526
0+110	18.10.2016 08:52:06	41.0167200	28.9753056	0	423	A-1526
0+160	18.10.2016 08:52:21	41.0165825	28.9758644	25	424	A-1526
0+190	18.10.2016 08:52:36	41.0164528	28.9761848	0	424	A-1526
0+240	18.10.2016 08:53:07	41.0162600	28.9767227	31	425	A-1526
0+330	18.10.2016 08:53:23	41.0159500	28.9777300	0	426	A-1526
0+460	18.10.2016 08:53:38	41.0159073	28.9793186	55	427	A-1526
0+730	18.10.2016 08:53:53	41.0161629	28.9825363	65	430	A-1526
1+210	18.10.2016 08:54:24	41.0147667	28.9871941	66	435	A-1526

As shown in Table 3, there are some long distances between each two consecutive data after assignment process and it is not known what the speed of the vehicles are in these sub-segments. Due to this reason, the Cubic Spline Interpolation (CSI) model as shown in Equation 2 [25] was used to estimate the speed of the vehicles in these sub-segments. Here, $P_i(x)$ is a third degree polynomial $(i = 0, 1, \ldots, n-1)$, x_i are known values of a real-valued function $f(x)$ at the $n+1$ pairs of data points $[(x_i, y_i), i = 0,1,\ldots,n]$ at which the values of $f(x)$ are known, α_i are coefficients of polynomial. CSI method has been chosen because it reveals the acceleration and deceleration movements of the vehicle more realistically in the time-speed graph for a vehicle. The method was implemented easily thanks to NumXL which is a time series add-in for Microsoft Excel.

$$P_i(x) = \alpha_{i,0} + \alpha_{i,1}(x - x_i) + \alpha_{i,2}(x - x_i)^2 + \alpha_{i,3}(x - x_i)^3 \quad (2)$$

After this interpolation process, all rows (i.e., blank information corresponding to each kilometer-stone) for a vehicle moving along the route had been completed and a sample about it is shown in Table 4 (3rd and 5th column of the table). This process was carried out for all of 58 buses moving in Eminönü-to-Zeytinburnu direction on 18/10/2016.

48 of 58 bus trips were used to analyze because these vehicles were operated regularly on the route and reliable records have been obtained. But it is not possible to say the same for the remaining 10 trips. Because, on these trips, there had been remarkable deviations from the route and significant missing data or dramatic errors in the records (such as reading the same location for minutes, reading the same speed value continuously). Location-speed graph of all 48 bus trips during the day is shown in the Figure 5.

Table 4. Sample interpolated data for a vehicle with # of Gate that A-1526

Km (1)	Date_Time (2)	Speed (km/sa) (3)	Date_Time_Interpolated (4)	Speed_Interpolated (km/sa) (5)
0+010	18.10.2016 08:51:50	33	18.10.2016 08:51:50.00	33.00
0+020	*	*	18.10.2016 08:51:51.36	28.07
0+030	*	*	18.10.2016 08:51:52.73	23.23
0+040	*	*	18.10.2016 08:51:54.14	18.60
0+050	*	*	18.10.2016 08:51:55.58	14.26
0+060	*	*	18.10.2016 08:51:57.09	10.31
0+070	*	*	18.10.2016 08:51:58.67	6.86
0+080	*	*	18.10.2016 08:52:00.33	4.01
0+090	*	*	18.10.2016 08:52:02.10	1.85
0+100	*	*	18.10.2016 08:52:03.98	0.48
0+110	18.10.2016 08:52:06	0	18.10.2016 08:52:06.00	0.00

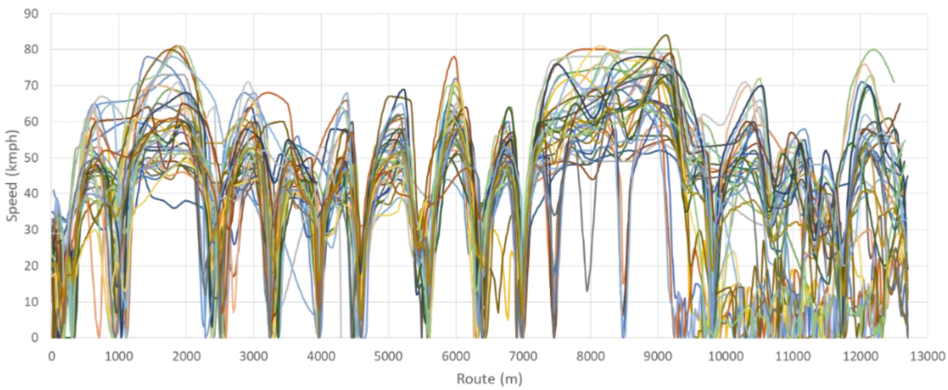

Figure 5. Location-speed graph for all trip all-day

3. ANALYZE, RESULTS AND DISCUSSION

The methods described in the previous section (cleaning incorrect data, completing missing data) were applied to all bus AVL data in the study area. Then, the average speed, standard deviation and variance of the vehicles operated along the selected route at AM-peak, PM-peak and all-day were computed for all sub-segments. The location-speed graph of the buses operating in the AM peak hours (between 07:00 and 10:00) is shown in Figure 6. As it is seen, significant decreases were recorded in the speed of the vehicles at bus stops and signalized sections. Also, the statistical analysis (mean, standard deviation and variance) of the measurements at the same hours are seen in Figure 7. While the mean speed is fallen in the bus stops and signalized sections, the standard deviation and the variance peaks in these sections. From this point of view it is possible to deduce: If the location of the bus stops and signalized sections are known, the sites where the variance increases and peaks out-off these sections are described as bottlenecks. Because the expected situation is that buses generally travel at a certain average speed in normal traffic conditions, except for these sections.

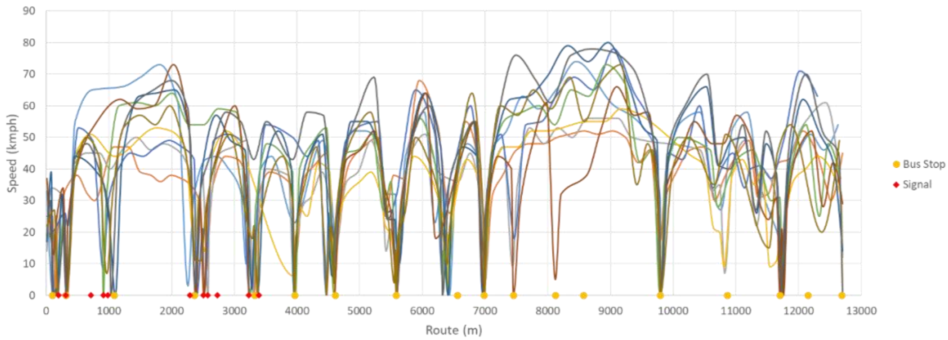

Figure 6. Location-speed graph of the vehicles serving in morning peak hours

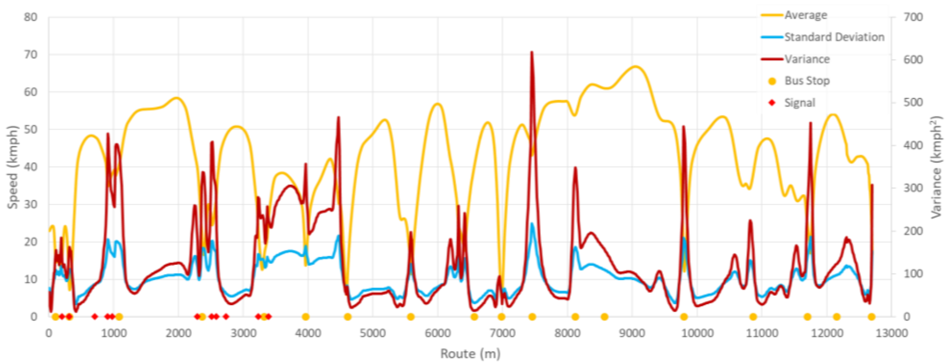

Figure 7. Average speed, standard deviation and variance for the vehicles serving in morning peak hours

In Figure 6, it can be easily seen that the buses moving on this route during the morning peak hours did not have to stop except for the bus stops and signalized sections, or there was no significant decrease in their speed. Therefore, no significant change was observed over the traffic flow in the direction of Eminönü-Zeytinburnu during AM-peak. However, as can be seen in Figure 5, extraordinary changes were observed during the day. Especially in the evening peak hours (between 16:00 and 19:00), it was determined that the bus speeds decreased significantly after 9100th meters (Figure 8) and this effect continued until 22:30 after the PM-peak. Between 9+100-12+350 kilometers, it had been observed that the average speed decreases considerably in the evening hours, and the variance creates a great number of peaks according to AM-peak. In other words, there is a continuous irregularity in deviations from the mean. This situation can be seen more clearly in the variance graph (Figure 9) obtained from the values measured all-day. The average speed and variance graph for the evening peak hours and the all-day is given below.

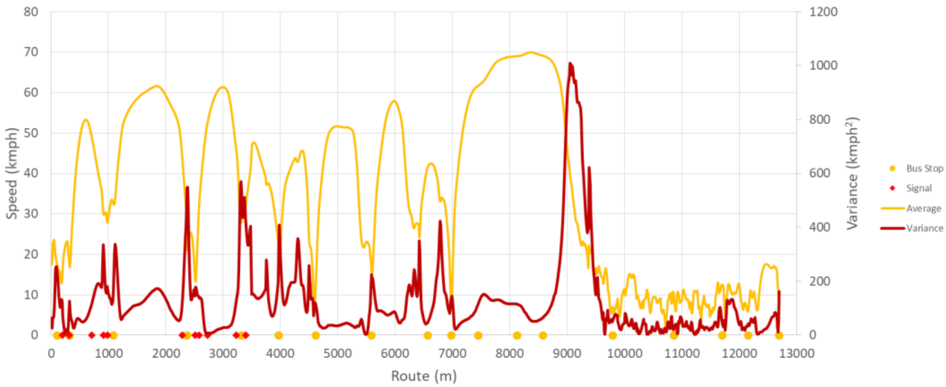

Figure 8. Average speed and variance for the vehicles serving in evening peak hours

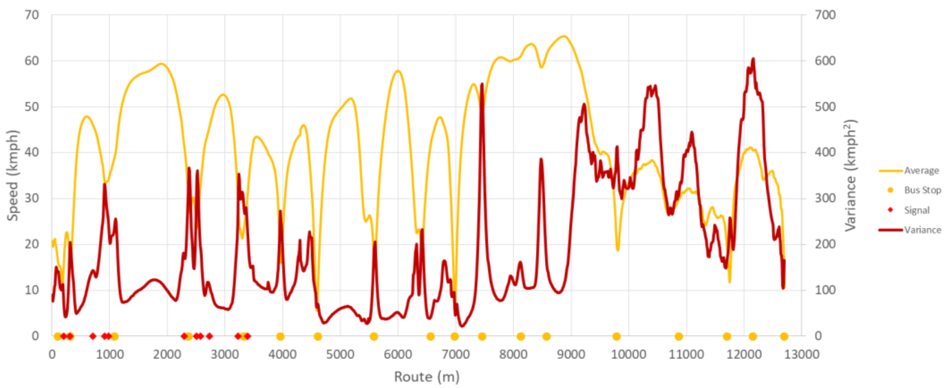

Figure 9. Average speed and variance for the vehicles serving all-day

Figure 9 shows that there are significant deviations from the mean at certain segments within a day, and so, the variance is quite high. This reveals that there is congestion, in other words, bottlenecks in these sections during the day. Because the variability in vehicle speeds was very high all day long. Buses were able to be driven at a certain mean speed at specific times of the day but sometimes moved quite slowly.

In the section which bottleneck occurred (9+100-12+350) variance value is calculated as a minimum 150.98 kmph^2 at km 11+670 and a maximum 604.84 kmph^2 at km 12+160. The highest variance was seen around the Sümerbank bus stop. The bus stop gave the highest variance value due to both the low-frequency usage and the high traffic volume in this section. Since the Sümerbank bus stop was not used frequently except during peak hours, the average speed is high here, while the average speed was low during heavy traffic conditions.

In the aerial photo given in Figure 10, sections with bottlenecks are seen. While the green color shows the segments with less variance, i.e. the fewer variability in speed during the day, the variance towards red is very high and bottlenecks had occurred in these segments.

Figure 10. Change in variance along the route

4. CONCLUSION

The aim of this study is to detect the bottlenecks by using the data obtained from the GPS based AVL system integrated into the tire-wheeled public transportation vehicles. To summarize, in order to prepare data for analysis on the selected route, the following steps have been applied:

- AVL data for each bus was transferred to the GIS, then bad and off-route data were cleaned,
- The route link was drawn and then split into 10 m long sub-segments with GIS,
- Kilometer-stones and location information of the each sub-segment were identified via GIS,
- Each AVL data were assigned to the nearest kilometer-stone with the codes written in the Excel VBA,
- Empty cells (speeds at the kilometer-stones) without AVL data were filled by CSI method for each bus along the route.

Thus, changes in the speed of all bus along the route could roughly be estimated (Figure 5). So, the data were made prepared for statistical analysis.

When looking at the location-speed graphs of the vehicles, it is clearly seen that the speed decreases pretty at the bus stops and signalized intersections. Similarly, it is distinct that the standard deviation and variance peaks in these areas. This inverse relationship between speed and variance suggests that: the significant increase in variance, except for bus stops or signalized sections (including signalized and unsignalized intersections), can be regarded as an indicator of a bottleneck in ordinary traffic because of significant changes in vehicle speeds. Considering Figure 10, when the vehicles operating all day long are regarded, the sections where the variability in speeds are high and therefore the variance is high can be seen more clearly. As a consequence, buses operated at mixed traffic are directly affected by changes in traffic conditions and hence this study shows that it is possible to deduce for general traffic from the information obtained with AVL data.

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