GHOST: A Novel Approach to Smart City Infrastructures Monitoring Through GNSS Precise Positioning

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Abstract— **The purpose of this research is to present a telematics platform which aims at addressing emerging problems of modern cities and relevant needs in terms of urban planning and maintenance. Many cities are today engaged in massive investments for infrastructure development and maintenance across many structural elements including lighting, traffic and transportation systems. In this context, leveraging the use of ICT in public transportation systems is key asset to enable the "urban innovation" bringing research results into real solutions for the smart cities in order to provide benefit for the citizen. To address the aforementioned needs, the authors propose GHOST ("Galileo EnHancement as BoOster of the Smart CiTies") a Location-Based Service (LBS) based on European GNSS (E-GNSS) and SBAS advance positioning. The goal of GHOST is to implement an Intelligent Transport System (ITS) for the public transport which is able to exploit the geo-referenced information of urban elements along the bus lines, monitoring them in a smart, continuous and autonomous way.**

Keywords— smart cities; infrastructure; monitoring; GNSS; Galileo; EGNOS; positioning; sensors.

I. INTRODUCTION

Concept of smart cities is a process, by which cities become more "liveable" and more responsive to new challenges by investing in human and social capital and in transport and ICT infrastructure. Strictly speaking of the ICT infrastructure that a Smart City [1] can adopt, a primal asset are sensors, including wireless sensor networks and the Internet of Things technologies which are used to monitor many aspects of a city in real-time or near real-time, including traffic, power networks, street lighting and water/sewage systems and garbage collection [2-3].

The solution proposed in this work clearly fits within the category of ICT infrastructure improvements: GHOST ("Galileo EnHancement as BoOster of the Smart CiTies") is Location-Based Service (LBS) based on the European GNSS (E-GNSS) advance positioning, which aims at implementing an Intelligent Transport System (ITS) for the vehicles of public transport networks. GHOST is based on the deployment of a dynamic wireless sensor network collecting geo-localized environmental image-data through an on-board vehicular system, managing and processing them through a back-end image processing engine, and providing results in real-time to the city managers through a web dashboard.

As shown in Fig. 1, the vehicle On-Board Unit (OBU), equipped with an EGNOS/GALILEO [4] enabled receiver and an on-board camera, automatically takes snapshots collection of POIs during the normal operations on the bus lines and regularly transmits these frames to a centralized database platform. Pictures are processed, at the back-end side, by advanced image processing algorithms in order to identify relevant contextual information and delivered to interested users, which can be public administration, garbage collector or police departments, with the objective of:

- Report street lighting anomalies or road deteriorations;
- Monitor road deterioration level (e.g. potholes); and
- Detect doubled parking or occupied parking reserved for disabled drivers by unauthorized vehicles.

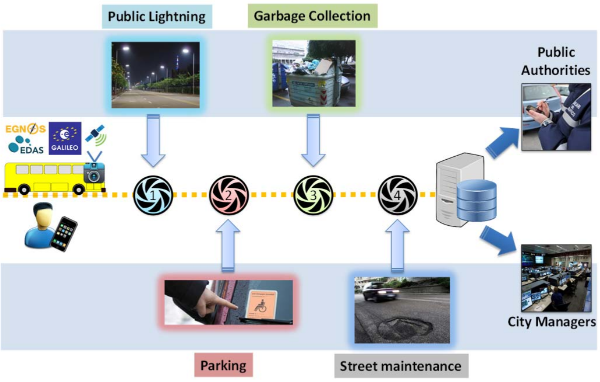

Fig. 1. GHOST System potential Use Cases, Users and Stakeholders

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This research project was partially funded under the European Union's Horizon 2020 Programme under grant agreement no 641495 — GHOST

Lots of new systems were recently developed for monitoring elements of urban environment: an example is given in [5], where software for tablet-devices equipped with a camera and a GPS, is able to provide on-site recording and monitoring of the status of road asset infrastructure such as cracks, potholes, etc. Collected information is held in a road reference database, and results can be visualized on open source maps.

With respect to this and others solution available on the market, the advantage of GHOST system is the capability to perform in total autonomy, taking “the right snapshot at the right time” [6]. While a human user can easily react at an error range of 10-20 meters for an LBS application, by facing the last meters incertitude thanks to the environmental context, the automatic GHOST solution guarantees an error from 1 to 10 meters (depending on POI’s size) in order to trigger the snapshot without facing the risk to miss the POI. Moreover, the GHOST system is designed to provide a multi-purpose, flexible and solution which can be easily adapted to cover disparate use-cases such as road, parking and garbage monitoring but also disparate scenarios of interest in the urban environment (i.e., bus stop, vending machine, advertisement monitoring, etc.)

Such level of service, in a severe urban environment, is only achievable thanks to the exploitation of modern GNSS technologies and lower costs of data connectivity. Joint usage of GPS/GLONASS/GALILEO [7] and SBAS substantially contributes to a better and more robust identification of a specific location bringing several benefits including:

- Better availability of positioning service in urban canyons, with very low dilution of precision and positioning using stronger satellite signals;
- Integrity with the support of EGNOS services as input for Kalman filter – hybrid GNSS/IMU solution [8].

The GHOST concept is also extended to voluntary citizens that may also contribute to this smart city loop by collecting snapshots using smartphones when they are detecting any anomalies on city infrastructures.

This paper will present results from test and validation phases to demonstrate the applicability of the solution in a real operational scenario and on several representative use cases.

II. GHOST SYSTEM ARCHITECTURE

A. Overall Architecture

The GHOST system includes five main communication and functional entities (Fig. 2): Web-portal and Database, Users and Administrators Dashboard, Image Processing Server, Embedded Device (OBU) and Citizens Smartphone Application. Users and administrators can access the GHOST web portal over the Internet and “data collectors” (vehicle embedded system and citizens) can use 3G or Wi-Fi to communicate information to the back-end web portal.

The web portal allows users and administrators to view and interpret the acquired data (snapshots) and to configure all the aspects of the images collection (defining POIs, categories, etc.). It provides user access to the database and handles the incoming automatic snapshots from the OBU and those received from the citizen Smartphone Application, both of which are sent to the Image Processing Server for their interpretation prior to be made available to the users.

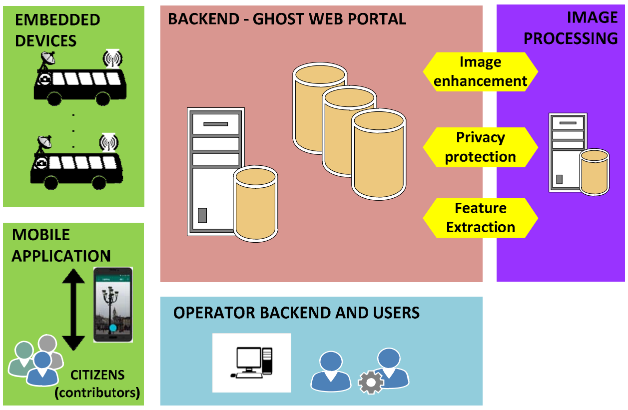

Fig. 2. System Architecture

B. Embedded Device

The Embedded Device (OBU) purpose is to collect high-quality snapshots of accurately and robustly localized POIs and to transfer raw or pre-processed images to back-end database. Data transfer is done over cellular or Wi-Fi network depending on type of service provided and appropriate associated data traffic costs. The OBU’s built-in logic is able to select and use one of the two cameras depending on POI position and angle of arrival of a vehicle relative to POI. To simplify further upgrades, the OBU is designed as a modular system with sufficient processing power for fusion of the inertial sensors and GNSS solution.

C. Navigation Solution – Status and Limitations

Proposed system uses GNSS-based positioning for triggering operation of mobile cameras, making positioning accuracy and availability the key drivers of the overall service quality. Modern multi-constellation GNSS receivers tend to provide meter-level accuracy [9] even in regular urban conditions, with high signal availability for most of the time.

To better clarify opportunities offered by these technology, we will briefly summarize the performance of modern low cost single positioning GNSS receivers.

Nowadays’ GNSS signals availability ensures that receivers at near open-sky conditions can track 15-25 satellites simultaneously, with the DOP levels very close to one for more than 90% of time. According to planned E-GNSS development, this should further increase in the coming years, with the maximum of 30-40 visible satellites in some regions after year 2020 [10]. Additional commodity brought by the last generation of low-cost single-frequency receivers, is high update rate of the navigation solution, which reached 10-20 times per second. With the very small processing delay, modern receivers calculate speed and position every 50-100 milliseconds. Considering usual maximal vehicle speed in urban environment, which rarely exceeds 15-20 m/s, vehicle can be located at every meter along trajectory. It is a common understanding that GNSS signal may be corrupted by various external interferences, multipath and variety of obstacles. Still, GNSS signal enables different kinds of observations [9]. Speed and position are often estimated via independent algorithms based on pseudo-ranges and Doppler measurements. The nominal accuracy of the speed vector is usually at the much higher level – 0.01-0.05 m/s [11], but also prone to errors due to multipath and switching of the used satellites. This redundant information can be further improved by including vehicle non-homonymic constraints. Typical constraints are speed limits along lateral and vertical axis of a vehicle [12]. Finally, different estimators could be used to benefit from this redundant information and to smoother position solution. With the help of SBAS (Satellite Based Augmentation Systems) such as EGNOS in Europe, receivers can utilize additional signal corrections and users can really experience positioning accuracy close to a meter-level even with the low cost GNSS receiver. There is a huge potential in exploiting this increase in the navigation accuracy in smart-city applications.

Besides, the core GNSS positioning potential issues, the several other error sources that may degrade system performance are:

- *POI definition position error*. It is a map-dependent source of error which can easily reach few meters mainly due to human factor. Most of the city central-area maps have a very fine level of details, and this potential error should further decrease in the future. Even if impractical, this error could be avoided by one-time-only on-field positioning with high quality GNSS receiver. Value of this error is time-invariant.
- *Processing delay*. It may become prevailing error if it is not properly managed. Mostly consists of GNSS processing delay and camera triggering delay. GNSS processing delay of 0.1 s induces 1.5 meter position offset at 15 m/s speed. It may be predicted or reduced by integration with inertial navigation (IMU) as it provides higher output data rates.
- *Level-arm offset*. In general, camera and the GNSS receiver are not collocated. Each installation needs to address this difference [13].
- *Change of the POI position*. Such as variations in vehicle position on a parking place or some other movable asset. Formally, this is a system-independent error, but it does impact on the quality of the service. It could be modeled as a slowly-varying noise component.

TABLE I. TYPES OF ERRORS THAT AFFECT SYSTEM ACCURACY

Error source	**Main characteristic**
GNSS error	Depends on location and time
POI definition error	Time-invariant
Processing delay	Influence is proportional to vehicle speed
Level-arm offset	Systematic-error, may be compensated
POI movement	Noise

In ideal conditions, the Embedded Device would capture a single snapshot from the optimal distance, with appropriate camera directivity and focus. In the real world, which includes already described system inaccuracies (but also vibrations of this moving platform, possible occlusion by other vehicles or objects, etc.) it is recommended to capture multiple snapshots.

Another potential issue is that the system cannot predict the exact bus route at each pass (which, in the case of cable cars or trains, is mostly fixed). In other words, the embedded system is not aware of the bus route, but just of the exact locations of POI. Therefore, it cannot predict the suboptimal location at each pass to take a snapshot until bus starts leaving this POI. For these reasons, we propose a two-stage mechanism (Fig. 3). At the first stage, when mobile camera is approaching the POI, system is taking up to N photos, considering speed and current bus location. This N could be configurable, and we propose up to 10-15 photos at each pass. At the second stage, which starts after leaving the area of interest, decision algorithm selects a smaller set of three images: this is the final set of snapshots to be transferred to GHOST web portal.

The snapshot selection logic takes into account distance from POI, vehicle speed, vibrations, quality of satellite signal and minimal distance between the photos. Historical data, collected at previous bus mission, can be also used to augment decision logic as they can contain additional indicators (e.g., number of road lanes). At the end of this process, final set of images with required metadata are archived and transferred using SSH File Transfer Protocol (SFTP).

D. Mobile Application .

The aim of the GHOST Smartphone Application is to involve citizens in the GHOST system, providing a reporting tool to capture in real-time contextual information (e.g. pictures, textual data) about the different elements of the urban landscape (e.g., lighting, road deterioration, parking, etc.).

Through the GHOST Smartphone Application (Fig.4), citizens can be involved, on a voluntary basis, in the process

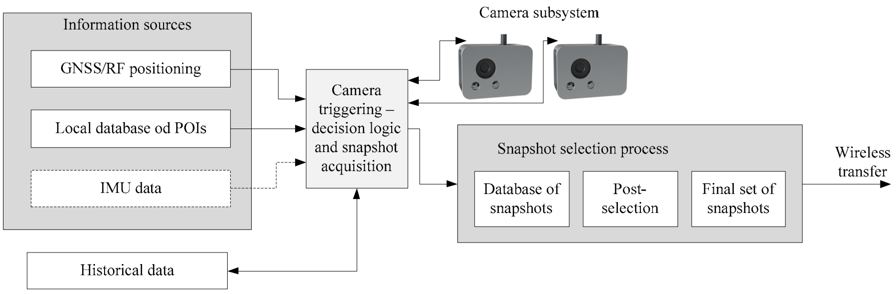

Fig. 3. GHOST image acquisition process.

of city environmental monitoring. With this application, they are able to subscribe to GHOST system, get information about available POIs, take snapshots at the specific POIs, and send them to the web portal together with a message or a comment about the status of the specific urban element.

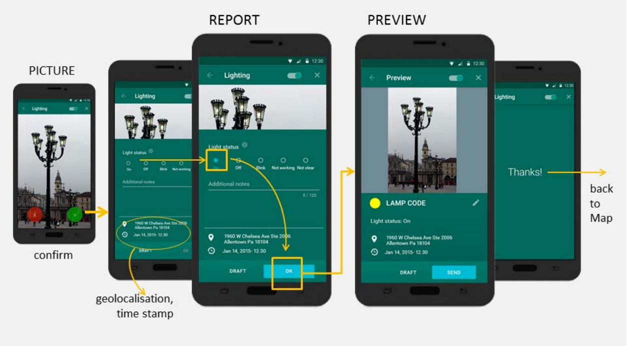

Fig. 4. GHOST Mobile application (in reporting lighting anomaly use case).

In order to reduce the uncontrolled and unmoderated upload of snapshots from the citizens to the GHOST Back-end, thus the increase of storage occupation, the Smartphone Application includes control mechanisms to prevent the camera to take a snapshot if the distance of the user from the POIs overcomes a predefined threshold (fixed at 10 meters).

III. GHOST VALUE PROPOSITION IN THE SMART CITY MARKET

GHOST provides an intelligent, efficient and autonomous system to monitor the urban infrastructures within a Smart City, helping city managers, involving citizens and creating value for the users in terms of:

- *Increased performance*, improving the usability and the availability of a city's infrastructures (e.g. parking spaces, roads, etc.) by enhancing and accelerating the control processes executed traditionally only by dedicated inspectors/ patrols; and
- *Cost reduction*, helping city managers to reduce the costs of monitoring the conditions of cities infrastructure or to extend the area under control leveraging the existing transportation network without incurring any high investments.

Instead of a continuous camera operation, which would generate huge amount of data to be analyzed by the city administration and maintenance services, GHOST tends to use a "smart-data" paradigm: only the right data – time stamped snapshots taken at the right location, are sent over the communication link to be further processed and analyzed and stored. This approach helps to decrease the amount of transferred and stored data with the following pros:

- Transferred images can be of a very high quality with very low compression ratio;
- Wireless data links are used efficiently as only relevant data are sent to the backend database (similar video streaming service would rapidly increase wireless transfer cost and time spent for image inspection and processing);
- Data transfer high quality images with real-time performance;
- Reduced storage requirements on the back-end side;
- Higher quality of final data processing and analysis with the same effort, either by computers or humans.
- Inspection of significant portion of primary road network multiple times a day by deploying OBUs to the limited number of buses. In case of city of Belgrade, Serbia this is equivalent to monitoring of up to 600 km of city streets.

IV. FIELD TESTS

In order to perform test and validation activities, the custom designed OBU, shown on Fig. 5, was installed in the public bus route indicator compartment. The OBU uses a NV08C-CSM GNSS module [14] with the external antenna. The system collected images using two IDS XS2 [15] cameras mounted on different positions.

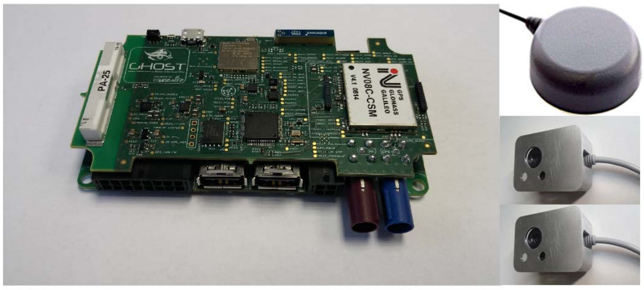

Fig. 5. Embedded system components (designed by Bitgear)

Initial field-trials show that the achieved GNSS positioning accuracy is below a street lane width, which is a key service enabler. In most of the cases of interest, in a dense urban environment, city streets have 1-2 road lanes of 3-3.25 m width. This biases camera-to-POI distance at some passes of the on-board GNSS receiver and the camera along the predefined POI. Cameras were triggered depending on bus instantaneous speed, measured camera distance to POI and angle of arrival of the cameras considering their orientation. Camera activity was limited to extend equipment lifetime. At the regular bus speeds within city, number of snapshots rarely exceeds 5-7 at one pass along any POI. As described in chapter II, this set of snapshots was further reduced to 3 images in by the post-selection process. Post-selection reduces wireless link costs, required storage, processing requirements and enables city managers and end-users to access a smart and filtered set of data.

System operation will be first illustrated via two examples with the different number of road lanes. Both examples represent automatic detection of illegal parking on places reserved for disabled people as one of the most demanding use case scenarios.

A. First Test Campaign – Suburban Environment

At the first example, a parking place near a two lane street was set as POI (Fig. 6). This use case envisions detection of a blue badge on the car windshield. It is crucial to enable camera triggering at the minimal achievable "working distance" from the POI to allow successful feature recognition on the image processing server. Results were gathered during two consecutive days. Since tests were performed in a suburban scenario with the tree canopy as the only obstacle, the satellite visibility was in range of 19-26 satellites. The position of the mobile on-board unit at the moment of the camera triggering within area of interest are shown as traces on Fig. 6. Ten consecutive passes were analyzed, measuring the closest captured position between the camera and the POI. Its average value was 3.5 m with a standard deviation of 0.8 m (Fig. 7). Vehicle speed has been varied at different passes up to 15 m/s. One of the measurements was filtered out as an outlier due to a different vehicle trajectory.

B. *Second Test Campaign – Urban Environment*

At the second illustrative example, shown in Fig. 8, the same positioning and triggering algorithm was evaluated at the dense urban environment at the four lane street. Test lasted for five consecutive days. According to gathered results, the camera distance to POI was dominantly affected by POI definition error and switch between the two road lanes. At the 20 analyzed passes along POI, the average minimal camera-to-POI distance was 8.8 m. The absolute minimum in this example was 5.1 m, which indicates strong bias component caused by POI definition error due to map-inaccuracy in the selected urban-canyon. The measured standard deviation of the closest measured distance from bus route to POI was 2.02 m, which includes ambiguity caused by additional street lane. The vehicle speed at the moment of camera triggering was in range 7-15 m/s. The average satellite visibility was 18.

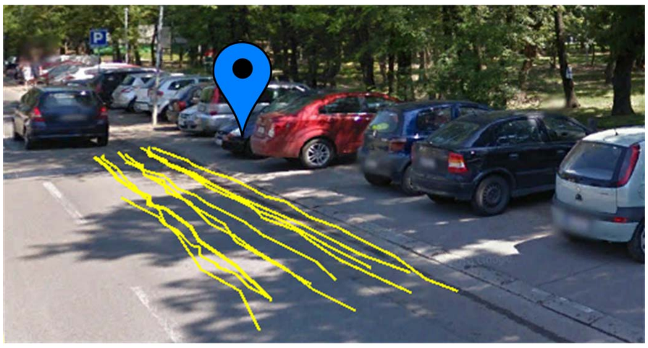

Fig. 6. Example 1 – POI and "traces" of the vehicle in the area of interest

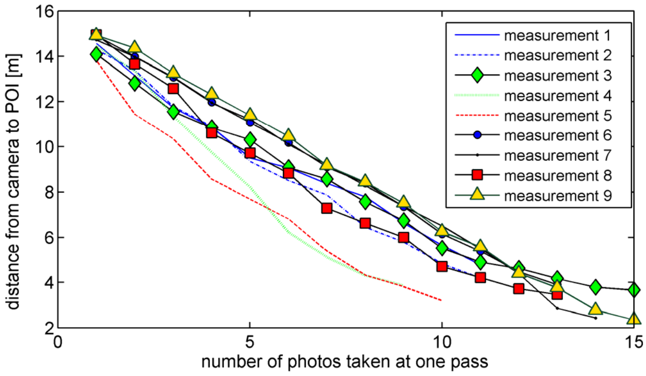

Fig. 7. Example 1 – Distance to POI at the camera triggering moments

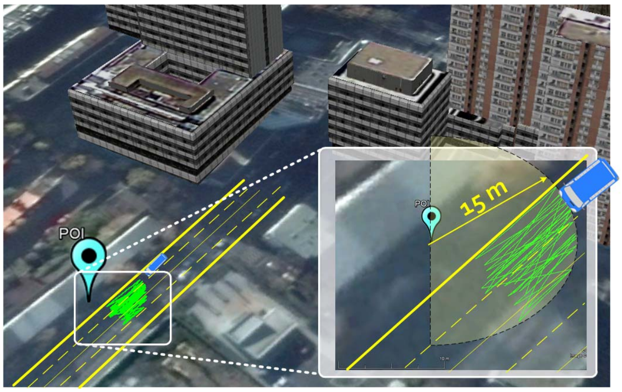

Fig. 8. Example 2 – POI and "traces" of the vehicle in the area of interest

C. *Achieved Image Quality*

During the test campaigns, we have used 5 megapixel cameras, installed as shown on Fig. 9. As image quality depends on camera intrinsic/extrinsic parameters [16] (e.g. focus, distortion, shutter speed, optics etc.) and also on the vehicle speed, the environment and the amount of light, we will not deeply analyze this area. Still, it is worth highlighting that, at the first example, with an approximate camera "working distance" below 4 m and an angle of view of 60^0, the expected "smallest feature" at static conditions for this type of camera is roughly 3 mm. At the second example, with a "working distance" of 8 m, the expected "smallest feature" gets worse increasing to roughly 6 mm. These numbers are illustrative examples of the current image acquisition capabilities, but the tests results clearly show that the key element for the proposed solution – in one of the most demanding use case such as parking place inspection – are still the further improvement of positioning algorithm and better POI definition.

a) b)

Fig. 9. Example 2 – a) Camera mounting position; b) one of the real camera snapshots taken from a mobile on-board-unit at 12m/s

D. *Long-term Testing at Operational Environment*

Finally, to validate system performance over longer period of time at real operational environment, we have carried out field test campaign in the city of Belgrade over 30 days. Eight different POIs were monitored at more than 260 passes of bus along the route over this period. Three types of POIs were included – parking places, advertising billboards and garbage collection points. Six of the POIs were next to the four lane street, and at two cases, the bus was using two lane streets. All results were obtained from mobile platform at speeds 7 - 15 m/s, except at one POI where typical bus speed was in the range 2-7 m/s. Camera triggering mechanism was based on verification of distance to POI, bus heading and velocity. Images were acquired at 1829/2072 passes along POIs, i.e. success rate of the triggering mechanism was 88% and varying from 77 to 99% for different POIs. This percentage includes drops due to road-maintenance activities and it reflects potential quality of service in exploitation. Over monitoring period, the average minimal measured distances between the camera and the POIs, as defined on map, were 3.6 to 9.6 m, with similar median values. Standard deviation of measured minimal distances was between 1.8 and 3.1, with significant influence of the street lane changing. This confirms lane-level positioning accuracy at urban conditions. System performance which is closely coupled with the final quality of captured images might be degraded on multiple-lane streets. This is further analyzed on Fig. 10 which shows the closest achieved distance between the camera and one of the POIs on a four lane street at 220 passes of a bus along this street. For this specific case, the average distance between bus and the POI was 4.3 m and 8.7 m depending on used street lane.

TABLE II. FIELD TEST CAMPAIGN RESULTS

POI number:	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**
Image capture success rate[%]	93	**99**	79	85	88	**77**	94	88
Average min. distance [m]	**3.6**	8.2	7	8.8	6.6	8	6.7	**9.6**
Median min. distance [m]	**2.5**	8.2	6.6	8.8	6.6	8.1	6.6	**9.4**
Snapshots < 10 m [%]	78							
Snapshots < 5 meters [%]	28							

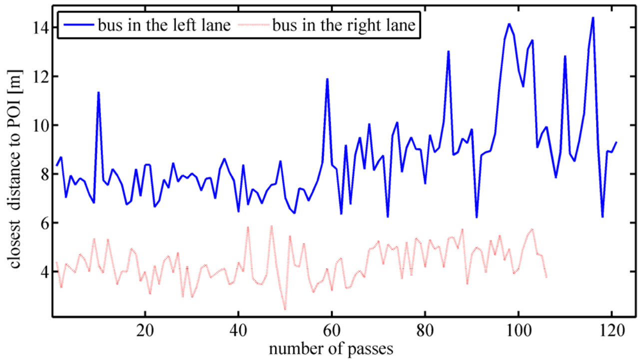

Fig. 10. Minimal achieved distance to a selected POI at four-lane street

V. CONCLUSIONS

The GHOST system is a novel attempt for exploiting a huge potential of recent increase in the GNSS navigation accuracy in smart-city applications. We have presented overall system operational scenario and architecture, the main envisaged use cases and identified sources of errors that may affect quality of service. The initial field-test results show sufficiently accurate mobile camera positioning, triggering and snapshot selection mechanisms with an image quality that is appropriate for all envisaged types of services. Proposed solution enables cost-effective infrastructure monitoring suitable for cities of various sizes. Such a system, leveraging existing transport infrastructures, can hardly cover complete street network of any city, but it may provide very fast deployment and cost-effective service with costs shared between different stakeholders including private companies. The future step is to further test the system in diverse environments and to provide on-board image processing in real-time to allow the system to handle more dynamic scenarios such as bus lane infractions congestion charging enforcement, etc.

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