Urban Bus Positioning: Location based services and high level system architecture

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ABSTRACT

Today's urban transport systems are dominated by private vehicles, which are significant contributors to traffic congestion and pollution. This is expected to increase as the urban population grows, predicted to account for about 68% of the world's population by 2050. In comparison to private cars, transport systems dominated by buses produce lower traffic congestion and emissions. Therefore, improvements in bus operation activities most of which require information on bus location (i.e. location based services) should facilitate urban transport sustainability.

However, to date there is no agreement globally on the location based services, their location requirements and technologies to deliver significant improvement in bus operations. Therefore, this paper creates for the first time, a comprehensive list of bus operation services and specifies the performance requirements. These are considered together with challenging spatio-temporal characteristics of the urban environment to specify a high-level location determination system architecture for urban bus operations. The services, their requirements, standards and positioning system architecture are essential for the formulation of appropriate policies, regulation, service provision, and development and procurement of urban bus positioning systems.

KEYWORDS: Urban, Buses, Congestion, Location Based Services

1. INTRODUCTION

The world's population is predicted to grow significantly over the next decades (UN, 2017; UN 2018). Currently 55% of the world's population (4.2 billion) lives in cities. By 2050, the urban population will reach nearly 5.9 billion representing approximately 68% of the world's population, with 90% in cities in Africa and Asia. By 2030, the world is projected to have 43 megacities of more than 10 million inhabitants most in developing countries (UN, 2018). Without appropriate measures, the predicted surge in population is likely to be accompanied by increasing traffic congestion, air pollution, sprawl, energy use and pollution, presenting significant challenges to sustainability.

To address the problems associated with population growth and its impact on the transport infrastructure, improvement in bus systems (and hence operations) in the developed and developing cities has a potential as a cost-effective approach to facilitate the achievement of transport sustainability. In comparison to private-vehicle dominated urban transport systems, those that are largely reliant on buses produce significantly less congestion, lower energy consumption and emissions. This is because buses when full are inherently efficient both in terms of road space and fuel consumption per passenger kilometre. Depending on the type of bus (standard, articulated, bus-train or double articulated), a fully occupied bus can replace between 5 to 40 cars with a corresponding fuel saving ranging from 40 to 97% (UITP, 2015).

Furthermore, relative to the other public transport modes, buses are already the most widely used. For example, in the European Union in 2014, 57.6 billion passenger journeys were made using public transport of which 55.8% used buses, with metro systems accounting for 16.1%, tramways or light rail 14.5%, and suburban railway 13.6% (UITP, 2016). These potential benefits have spurred a speedy evolution in bus and related technologies, infrastructure, concepts of operation, business models and operations best practice or benchmarking, with increasing evidence that buses are a very appropriate mode to meet sustainability requirements. This is in terms of energy efficiency, emissions, space occupancy as well as operational effectiveness as buses are more easily adapted to passenger requirements and do not require heavy infrastructure. This is in addition to safety benefits as bus accident rates are relatively low compared to other surface modes. Particular areas of improvement have involved movement away from diesel and biodiesel buses, by far the largest part of urban bus fleet (90% in Europe) towards alternative fuels (e.g. hydrogen) and electric buses, development of new engines to comply with Euro VI diesel, accelerated bus renewal and substitution of old buses, and operations infrastructure including ITS (UITP,2015; Tozzi et al., 2016).

On infrastructure, there is a move towards segregated bus transport systems and improvement of intermodal connectivity (e.g. rail stations with fully closed or sheltered bus stops and direct connections to pedestrian and cycle routes). In addition, conventional bus stops are transforming into new bus shelters with CCTV and real-time display to increase security (and therefore customer satisfaction rate) and service reliability. In cities, to reduce emissions, many roads are being reallocated to allow only public transportation (and cycles) to alleviate traffic congestion and improve reliability. Other considerations include highway priority measures, enhanced passenger waiting facilities and pedestrian/cycling improvements in addition to higher efficiency traffic signal signalling technology (ARUP, 2018).

In onboard sensing, there has been a move away from reliance on bus drivers to detect pedestrians, cyclists, and motorcyclists, to using sensor technologies including radar and optics. Examples are CycleEye and Cycle Safety Shield. The former is an advanced cyclist detection technology which uses both radar and optical technologies to detect cyclists proximate to vehicles audibly alerting the bus driver to their presence. Cycle Safety Shield detects pedestrians, cyclists or motorcyclists proximate to vehicles, giving a visual warning and then an audible alert to the driver (TfL, 2014). Another example technology is the mobile eye with the capabilities for forward collision warning and, pedestrian and cyclist collision warning, headway monitoring and warning, lane departure warning, speed limit indicator and traffic sign recognition (SMMT, 2019). Other developments include automated passenger counting.

In operations, the key aspects of the operational strategies for buses include bus departure timetable management and bus stopping management. There has been a move away from a fixed departure time strategy or a strict time-based scheduling system to a flexible headway management strategy. Either the departure time is flexible and can reduce the possibility of clustering or a hybrid strategy is used where both departure and en-route management are effected (IBI, 2018; Chow, 2019). In bus stopping management, the conventional method is full route operation where every bus stops at every single stop, making the total journey time longer. There are several new operational strategies for bus stopping. Firstly, short turn refers to early termination of the bus. Secondly, limited stops refers to the skipping of certain stops with lower passenger volume. The combination of these two could reduce the bus travel time (Tang et al, 2018). In addition, Intelligent Transport Systems (ITS) are increasingly being used to provide amongst others real-time passenger information (RTPI) (Bullock et al, 2015; Eken and Sayer, 2014; Feng, 2018; Kunder et al 2019).

The evolution in buses summarised above are particularly evident in Europe where there have been several specific initiatives as described briefly below.

- The Zero Emission Urban-bus Systems (ZeEUS) project aims to extend fully-electric solution to the core part of the urban bus network composed of high capacity buses. ZeEUS adopts pure electric and electric-diesel hybrid engines, and it combines intelligent transportation systems technology, priority at junctions, and rapid and convenient fare collection, and is integrated with land-use policy in order to substantially upgrade bus system performance. The advances of ZeEUS include diesel fuel savings, reducing CO_2 emissions, greenhouse gas (GHG) emissions, SO_2 emissions, noise pollution as well as other pollutants.
- The European Bus-system of the Future (EBSF) Phase I and II projects aim to develop a new generation of urban bus systems by means of new vehicle technologies and infrastructures in combination with operational best practices. EBSF adopts energy management strategies based on both real-time and anticipation of the near future operating profile. Intelligent transport system-based operations are used to optimise interfaces between vehicle and platform to improve accessibility. The advances of EBSF

include environment (clean, low noise and zero emissions), ease of the flow of passengers and optimisation of dwell time.

- The Intelligent, Innovative, Integral Bus Systems (3iBS) project aims to develop a Roadmap for European Advanced Bus Systems research, define a work-plan for the exploitation of research results, and transfer most innovative concepts to a wider audience in Europe. 3iBS investigates electrification, compressed natural gas, biodiesel and biogas solutions. Furthermore, it realises a variable capacity by coupling and uncoupling single buses or trailers to buses. 3iBS uses plug /un-plug bus modules both during operation and at the bus depots to the kinematic chain of the vehicle.
- The Electrification of Public Transport in Cities (ELIPTIC) project aims to develop new concepts and business cases in order to optimise existing electric public transport infrastructure and rolling stock, saving both money and energy. ELIPTIC uses battery and hybrids charged buses, and they charge e-buses “en-route” (e.g. trolleybus operated on tram infrastructure) or on the spot (battery buses, hybrids charged from trolleybus, tram, metro network). The benefits include reduced fossil fuel consumption, improved local air quality through reduced local emissions, and advocating for an electric public transport sector at the political level.
- The OPTICITIES project partners from Sweden: Volvo, Chalmers, Göteborgsstad, Västtraffik, aim to develop genuine multimodal solutions based on reliable data for every mode and combination instead of a juxtaposition of mono-modal approaches exclusively focused on public transport. OPTICITIES use multimodal and predictive management to optimise urban networks.
- The Viajeo PLUS project aims to facilitate active uptake and transfer of knowledge and solutions, and provide the framework for the identification of the best solutions and effective mobility management. The main advance of Viajeo PLUS is to provide urban citizens with the best possible journey conditions and to optimize urban logistics operations
- The New tools for design & operation of urban transport interchanges (NODES) is a collaborative project co-funded by the Seventh Framework Programme focused on building and testing a Toolbox to support European cities in the design and operation of new or upgraded urban transport interchanges. NODES integrate land use planning with urban passenger infrastructure planning and upgrade efficient transport interchanges.
- The Information Technology for Public Transport (ITXPT) project aims to provide public transport authorities and operators with recommendations and requirements to support the purchase and integration of interoperable IT architecture. ITXPT defines interoperability on hardware, communication protocol, and service levels, and it integrates modules in a coherent architecture to simplify access to the market.
- The European Road Transport Research Advisory Council (ERTRAC) project aims to accelerate road transport research to deliver sustainable road transport and mobility of goods and passengers, the environment and European competitiveness. The main advances of ERTRAC include facilitating the exchange between cities on urban electric mobility solutions.
- CIVITAS is a network of cities dedicated to cleaner, better transport in Europe and beyond. Its main features are: electric and diesel engines, biofuels including biodiesel,

biogas and compressed natural gas. The main advances of CIVITAS include the innovative and sustainable delivery solutions for goods and services.

While the initiatives above, have the potential to improve bus operations, none addresses in a exhaustive way, the significant operational element that relies on Location Based Services (LBS) such as estimated time of arrival, bus priority at junctions, and in-situ (dynamic) environmental compliance monitoring. Conventionally, within ITS for location based services for bus operations, Automatic Vehicle Location (AVL) is responsible for the determination of the position, location and derivative information such as estimated time of arrival, while Automatic Vehicle Management (AVM) uses the AVL and other information to manage vehicles, drivers and service (e.g. regularity, compliance with schedule and data capture). Although there have been some studies on such systems and their applications (e.g. Parker, 2008, Porretta et al., 2009, Hounsell et al., 2012; SaPPART, 2015; Manela, 2016, Tilocca et al. 2017), they focus on specific aspects with the consequence that there is no agreed exhaustive and comprehensive list of applications or services for urban bus operations. Furthermore, the location requirements in terms of the four Required Navigation Performance (RNP) parameters of accuracy, integrity, availability and continuity are still to be specified and agreed.

Accuracy is a measure of the conformance of an estimated position solution to the true position at the 95th percentile. Integrity relates to the trust that can be placed in the correctness of information supplied by a navigation system. It includes the ability of the system to provide timely warnings to users when the system fails to meet its stated accuracy. Specifically, a navigation system is required to deliver a warning (alarm or alert) when the error in the derived user position solution exceeds an allowable level (alert limit). This warning must be issued to the user within a given period of time (time-to-alert) and with a given probability (integrity risk). Continuity is the capability of a system to provide the required levels of accuracy and integrity during a period of operation. Continuity risk is therefore, the probability of unscheduled interruptions during the operation. Availability is the proportion of time that a service is provided with the required levels of accuracy, integrity and continuity (Ochieng et al. 2003).

The RNP forms the basis for the specification of location determination technologies to deliver significant improvement in bus operations and hence ridership. Because of this lack of the RNP, the current location determination systems are inadequate with low levels of performance in terms of, for example, accuracy and integrity of travel time estimation. Therefore, to specify efficient technologies for location determination, it is imperative in the first place to identify the location based services and their RNP targets (Porretta et al. 2009).

Given the above limitations, the motivation for this paper is to contribute to the improvement of the efficiency of urban bus operations in three ways. Firstly, it identifies and defines a comprehensive list of location based services. Secondly, the RNP for each of the applications is specified. Thirdly, the RNP is used to specify a high-level architecture for the location determination system. The rest of this paper is structured as follows. Section 2 identifies and describes the LBS relevant to urban bus operations and creates the first comprehensive list. The RNP for the applications is addressed in Section 3. The applications and their requirements are used to inform the specification of a high-level urban bus positioning system architecture in Section 4. The paper is concluded in Section 5.

2. LOCATION BASED SERVICES

Literature review and a dedicated survey are employed to identify and define the Location Based Services (LBS) relevant to urban bus operations. The limited literature on this subject is in part addressed in the second instance by a dedicated international survey of the main bus operators to corroborate and augment the services determined from the literature review.

2.1 Literature review

Parker (2008) through a combination of literature review and stakeholder survey presents a useful analysis of the applications, technologies and benefits of AVL systems for bus transit. The benefits are discussed within the contexts of operations, maintenance, customer service, security, information technology, planning, revenue, marketing and training and human resources. The survey undertaken addressed the three areas of (i) technologies, timing and scale of implementation, (ii) issues experienced when designing, procuring, implementing, integrating and using AVL systems, and (iii) lessons learnt. Porreta et al (2009) identifies and presents the various location based services that could be supported by Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS). This is done within the context of a wider research on the impacts and mitigation of interference (intentional and non-intentional) with GNSS signals through jamming, spoofing, meaconing and signal attenuation. Hounsell et al. (2012), explore the management of large data generated by AVL systems with a case study of the London's iBUS system. They illustrate this with three online and two offline applications. SaPPART (2015) explores the issues of specification of the location determination requirements and testing of systems that provide positioning, velocity and timing information for a number of services that are provided through ITS. Manela (2016) focuses on the applications and technological solutions to urban bus operations that are underpinned by the London's iBUS system. Tilocca et al (2017) assesses the uses of real-time and non-real time functions based on AVL data with a case study of Cagiari's AVL system. The real-time applications are presented within the contexts of fleet management and operations, Bus priority at traffic signals, information for passengers. The non-real time applications are in the contexts of performance measurement, service planning and operations.

The limitations of the studies above is that they focus on aspects of AVL, without a holistic consideration of urban bus location based services, the required navigation performance and the corresponding positioning architecture. Therefore, an initial attempt is made below to consolidate (from the studies) the various location based services. From the existing sources, Table 1 presents the location based services relevant to urban bus operations together with the relevant stakeholders. Each is described in turn briefly below.

Travel time/Real-Time Passenger Information: This involves the estimation of bus travel time to various bus stops pre-trip with the necessary dynamic updates during trips. This service is crucial for bus riders, bus drivers and bus monitoring authorities. The information is communicated to the various stakeholders via appropriate media. This service underpins the Real Time Information (RTI) delivered to passengers via applications (apps), the internet, Short Message Service (SMS), countdown signs and on the bus.

Service Control: This service is used by bus operators for the management of headways and off-line intervention. It relies on the fleet management service functionality.

Fleet Management: This application is for fleet operators to optimise their operations (i.e. keep operations as normal as possible) particularly during incidents /accidents, and other safety and security related occurrences.

Bus priority at junctions/selective vehicle priority: This is required to enable seamless movement of buses through signalised junctions by giving priority to buses over other traffic. The buses transmit their position to a control centre which locates them on the road network and provides signal priority. This could be done for example, by extending or pre-empting the green phase at traffic lights, thus creating a green wave to significantly reduce delays. Such a service could be applied all the time, but more practically only for late running buses.

Low bridge warning: This service uses real-time bus tracking and low bridge position data together with communication methods to warn the driver that the bus is approaching a low structure or bridge. This is particularly crucial when a vehicle is diverted from its normal route (in service or while returning to the depot/garage).

Headway: The headway indication system in the bus cab displays information on the destination of the bus and the next stop for travelers not close to a sign on the road but close to a bus. In case of any change in the route, this service conveys the relevant information on the change.

Bus lane enforcement: This service uses bus positioning information to monitor and enforce adherence to bus lanes by bus drivers. Furthermore, bus drivers can report to service control, unauthorised vehicles using radio communications.

Dynamic route guidance/navigation: In this application, drivers input the location of the destination and in some cases the details of the preferred route into the on-board navigation computer which matches the current position estimation of the bus with the digital map via map matching (i.e. the use of an object's coordinates to determine its physical location on a map) (Ochieng et al., 2003). The navigation system then provides turn-by-turn navigation instructions and visual display to reach the required destination. Real time traffic information can be input as well as other factors that affect traffic such as weather conditions and forecasts, incidents/accidents and blocked roads.

Intelligent speed assistance: This application detects firstly through the position of a vehicle, and a Geographical Information System (GIS), the relevant attribute in terms of the speed limit on a link, and then compares it to the driving speed. It can either issue a warning or invoke a speed limiter if implemented or both. The link determination is through a positioning system and GIS where the former is responsible for the determination of the coordinates of the vehicle and the GIS is responsible for the physical location of the link and its speed limit.

Collision Avoidance: This application detects proximate traffic to avoid potential collisions in parking garages as well as en-route. A high update rate of position and velocity estimations could be used to detect and avoid collisions. The service works on the estimation of the states of the relevant vehicles and derivation of velocity and intervention through speed adaptation and/or warning the drivers. This application currently mostly uses camera/radar technology to issue warnings. There is the potential for GNSS (potentially augmented with the camera/radar) to be used particularly for enhanced collision avoidance between equipped vehicles.

Emergency/Incident Management: The requirements in terms of the location determination for a bus in distress is dictated by the needs of the emergency services in maximising the benefits of a response, e.g. reducing the impact of injuries or fatalities related to journeys.

Lane control: In this service, positioning, navigation and timing information are used to aid drivers in lane keeping in different types of roads, to improve safety. Lane keeping involves detection of irregular driving and raising alerts, and potentially automated intervention.

Environmental monitoring: With the increasing availability of low-cost portable Emissions Monitoring Systems (PEMS), this service would support such systems for in-service emissions monitoring by enabling the spatio-temporal referencing of the emissions data. Such data are useful in developing emission models and feedback to drivers on best driving practice to reduce emissions.

Restraint Deployment: In the case of an unavoidable collision, restraints are deployed for the safety of vehicle occupants, resulting in the reduction of the severity of accidents. In the event of incorrect decisions, this application could have significant safety and legal implications, hence, the required performance are inevitably stringent.

Performance measurement/operations monitoring: The data collected and the information gathered feeds into measuring and quantifying the Quality of Service Indicators (QSI) and performance monitoring models. QSI such as the Excess Waiting Time (EWT), lost mileage and driver compliance with schedules, form the basis for contracts granted to operators in some jurisdictions.

Table 1: Urban bus operations LBS – literature review

Service	**User group or stakeholders**
Travel Time / Real Time Passenger Information (RTI)	Bus riders, travel and traffic management and operators.
Service control	Operators
Bus priority at junctions/selective vehicle priority	Travel and traffic management and operators.
Low bridge alarms	Riders, drivers, traffic management and operators
Headway	Operators, traffic management and operators
Bus Lane enforcement	Traffic enforcement
Dynamic route guidance/ Navigation	Bus drivers, bus operators
Fleet management	Bus operators and managers
Intelligent Speed Assistance	Bus driver, bus operators /managers
Collision avoidance	Riders, Bus operators and managers, Fleet asset owners
Emergency / Incident management	Bus operators and managers, Fleet asset owners
Lane Control	Bus drivers and operators
Restraint Deployment	Bus drivers and operators
Performance measurement/operations monitoring	Bus drivers and operators

From the applications or services in Table 1, it is notable that there is no function dedicated to the real-time monitoring of the quality or integrity of the navigation solution, a key requirement for mission (e.g. safety) critical applications.

2.2 Survey of bus operators

In discussions with Transport for London, a questionnaire survey-based study was commissioned in 2016 and undertaken by the Railway and Transport Strategy Centre (RTSC) within the Centre for Transport Studies (CTS) at Imperial to conduct a confidential survey to capture the state-of-the-art in automatic vehicle location-based bus operations in 14 major cities around the world including London. The initiation of this study recognised that high performance bus location facilitated delivery of efficient operations.

The cities surveyed are members of the International Bus Benchmarking Group (IBBG), which is facilitated by the RTSC at Imperial College London. The IBBG is now in its twelfth year. Its current members are TMB Barcelona, STIB Brussels, Dublin Bus, IETT Istanbul, Rapid Bus Kuala Lumpur, Carris Lisbon, London Buses, STM Montreal, NYCT and MTA Bus New York, RATP Paris, KCMT Seattle, STA Sydney Buses, Singapore SMRT and CMBC Vancouver. All provide regular passenger public bus service operations in large urban areas. To date more than 15 years of (2001 to 2015), are available for 105 key performance related data items to create Key Performance Indicators (KPIs) in areas such as service availability, accessibility, reliability and quality, productivity, finance, safety and security, growth, learning and environmental performance. It took three years of iterative definition development to ensure comparability. The fifteen organizations of the IBBG are all urban bus operators in large cities. The original eight member organizations, from seven countries, were chosen on the basis of their similar characteristics. One of the selection criteria was fleet size, which was set to be 1,000 or more buses. Other criteria were similarities in the service characteristics, technological comparability, and the role of the operator within the city (Trompet et al, 2009; Trompet et al, 2018).

It was envisaged that the results of this survey would augment those of the literature review to compile a comprehensive list of LBS, define the corresponding performance targets and specify a bus location determination system architecture that meets the current and future LBS requirements. Therefore, the objective of the survey was to capture and analyse data on the current and future LBS, the performance measures and related monitoring methods and practices, and the current bus location determination systems. In line with this objective, and following consultations/piloting between the RTSC and the IBBG, the survey questions were formulated to capture: (i) the current stakeholders and the relevant applications, (ii) the different performance measures or indicators and the corresponding quantified targets (including the RNP), (iii) the different practices for tracking and monitoring performance, and detection and mitigation of performance degradation, (iv) the future LBS and the corresponding performance measures and targets, and (v) the bus location technologies used.

The questionnaires were dispatched to urban bus operators in 14 cities (including London). The overall approach for the study in terms of participation levels was (i) completion of the questionnaire, (ii) follow-up, (iii) teleconference, and if necessary, (iv) a visit. Table 2 presents the *anonymised* list of the cities and the corresponding participation levels, that received the questionnaires. Note that with the exception of London, the other cities requested anonymity in the usage of their data. Two of the operators did not participate, while a third was not able to participate as it does not have a bus positioning system.

Table 2: Bus operator participation levels

City	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Questionnaire	√	√	√	√		√		√	√	√	√		√	√
Follow-up	√	√	√	√				√	√	√			√	√
Teleconference			√	√				√		√			√	√
Visit									√					√

The scale of bus operations in the eleven cities is captured in Table 3 in terms of fleet size, passenger kilometres, vehicle kilometres, types of vehicles in fleet (standard, mini/midi, double decker and articulated)

Table 3: Scale of bus operations

Data Items	A	B	C	D	F	H	I	J	K	M	N
Total number of passengers (Million Passenger-km)	532	409	1026	2592	411	3427	2988	835	1667	1316	8000
Total distance covered (Million Vehicle-km)	43	27	56	111	27	249	180	74	99.0	92.0	534
Total number of vehicles in the fleet	984	675	989	2141	600	5707	4,656	1332	1,487	1469	9616
Number of Standard vehicles in fleet	603	511	0	1,647	477	4872	3768	564	888	1,067	2,704
Number of double-decker vehicles in fleet	0	0	986	0	0	0	0	0	334	0	6912
Number of articulated vehicles in fleet	304	158	0	494	90	835	677	737	265	247	0
Number of mini/midi vehicles in fleet	77	6	3	0	33	0	211	31	0	155	0

From the responses received, Tables 4 presents the current applications indicating the number of bus operators that currently employ them and the level of criticality (high or medium) of automated vehicle location capability. The level of criticality refers to the impact of location accuracy and associated confidence (i.e. integrity) on a given LBS. Hence, mission (e.g. safety) critical services have a high criticality level.

Table 4: Current applications - survey

Application/Service	**Operator (City)**											**Criticality High-H Medium-M**	Total
	A	**B**	**C**	**D**	**F**	**H**	**I**	**J**	**K**	**M**	**N**		
Travel Time / Real Time Passenger Information (RTI)												H	11
Service Control / Fleet Management												H	11
Incident Management												H	8
Network Performance												H	8
Traffic Signal Priority												H	8
Ticketing System												H	3
Fare System												M	2
Low Bridge Alarms												M	2
Audit of Compliance by the Transport Authority												M	1
Automatic Passenger Counting												M	1
Control Depot Leaving Times												M	1
Detection of Traffic Jam Hotspots												M	1
Eco Assist												M	1
Headway												M	1
In-Depot Bus Location												M	1
Monitoring Driver Behaviour												M	1
Schedule Optimisation												M	1
Closed Circuit TV (CCTV)												M	1
Total	7	5	7	5	4	7	7	5	5	3	8	M	

From the results, the following observations can be made.

- Comparing Table 1 and 4, the current applications from the survey do not include a number of established ITS applications including Bus lane enforcement, dynamic route guidance, intelligent speed adaption, collision avoidance, lane control and restraint deployment.
- Of the eighteen current applications, there is no single operator that covers them all, with the highest number of applications being eight.

- Most operators focus on the first five services (RTI, service control/fleet management, incident management, network performance and signal priority).

To facilitate the specification of a location determination system useful in the long term, the Survey also requested a response on what were considered by the operators as the future applications. As expected some of the operators identified some applications that were already in use by others. Excluding these, the following additional nine applications were identified by the operators: *automatic parking*, *automatic accident detection*, *disruption management*, *intelligent speed assistance*, *driving range (for electric vehicles)*, *restraint deployment*, *ticketing* and *predictive maintenance*. It should be noted that *intelligent speed assistance* and *restraint deployment* were identified in the literature review (Table 1). Another new application is *real time performance quality (integrity) monitoring,* identified as missing from the literature review. The applications from the literature review and the survey are collated in Table 5 to provide a comprehensive list of location based bus operations.

In addition to the applications from the literature review, the *Eco Assist* service facilitates efficient driving practices to improve fuel economy and reduce the impacts on the environment. Such practices are inherently location based. In the case of the *monitoring driver behaviour* service spatio-temporally referenced data (e.g. on speed, acceleration and idling) are captured and used to improve engine efficiency, safety and fuel economy. The *automatic parking* service requires real-time state estimation aided by spatial information and vehicle control. It has the potential to both reduce the time taken to conduct manual parking and accidents in the parking zones.

The *automatic accident detection* application informs the relevant stakeholders of the occurrence and location of an accident and its attributes. The information is conveyed to the stakeholders using terrestrial communication systems. The use of *CCTV* is mainly for the safety and security of passengers and drivers. The location and time of the occurrence of safety and security related incidents and accidents are vital in their reduction. The other applications are *schedule optimisation* (related to headway management), *in-depot bus location*, *driving range management* required for charging of electric vehicles, *predictive maintenance* through automated location based in-use bus inspection and *disruption management* enabling the dynamic recovery of operations at a pre-defined level following different kinds of disruption. Furthermore, the *fare* and *ticketing* applications require information on location and time for the determination of appropriate fares.

Table 5: Current and future LBS for urban bus operations

Urban Bus operation LBS	**Stakeholders**
Travel Time / Real time passenger information (RTI)	Bus riders, travel and traffic management and operators.
Service control / fleet management	Operators
Incident management	Operators
Network performance	Operators, regulators
Traffic Signal (Bus) Priority	Travel and traffic management and operators.
Ticketing system	Riders, operators
Fare system	Riders, operators

Low bridge alarms	Riders, drivers, traffic management and operators
Audit of compliance by the transport authority	Regulators
Automatic passenger counting	Drivers, operators
Control depot leaving times	Drivers, operators
Detection of traffic jam hotspots	Drivers, operators
Eco assist	Operators
Headway	Operators
In-depot bus location	Operators
Monitoring driver behaviour	Operators
Schedule optimisation	Operators
CCTV	Drivers, operators
Bus lane enforcement	Drivers, operators
Dynamic route guidance	Drivers, operators
Intelligent speed adaptation	Drivers, operators
Collision avoidance	Drivers, riders, operators
Lane control	Drivers, operators
Restraint deployment	Drivers, passengers, operators
Automatic parking	Drivers
Automatic accident detection	Drivers, riders, operators
Disruption management	Drivers, operators
Driving range (for electric vehicles)	Drivers, operators
Real time performance (integrity) monitoring	Drivers, operators
Predictive maintenance	Operators

The Required Navigation Performance (RNP) performance parameters of accuracy, integrity, continuity and availability defined in the introduction section originated from aviation and are now widely accepted globally as the performance measures for positioning and navigation systems for most applications including road transport. In road transport and in particular the provision of ITS services, it is critical that appropriate techniques are used to derive the performance requirements for the determination of bus position, velocity and time (PVT) from ITS service level requirements. This relationship is captured in Figure 1 in which the PVT data are used by the service/application module to deliver the service(s) to the users.

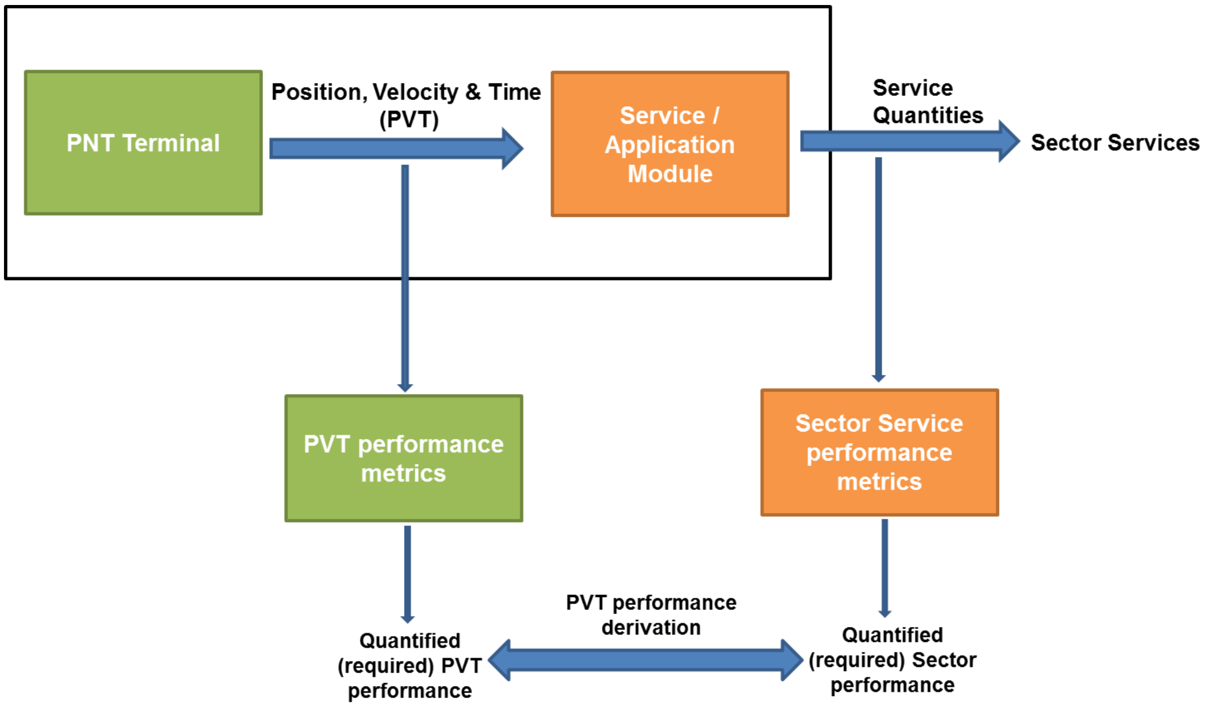

Figure 1: Relationship between service level and PVT performance

The requirements derivation process should be technology agnostic and account for operations/functionality, practical experience, human factors and mission (e.g. safety) criticality. This could involve the application of risk analysis techniques including Hazard and Operability (HAZOP) and Failure Modes, Effects and Criticality Analysis (FMECA) which are structured and systematic process for the examination of operations, process and/or systems to identify and evaluate failures and to quantify their impacts in terms of risk (Gould, 2000). The process enables performance budgets to be allocated to the different components of the ITS including the PVT platform. While work is progressing to quantify the RNP using these approaches, Table 6 presents initial results based on the consideration of the results of field experimentation, operational factors, human factors, level of mission criticality, the literature and consultation with a Subject Matter Expert (Manela, 2016).

For example, controlled tests undertaken by Transport for London (Manela, 2016) to quantify the accuracy of GPS using CCTV and accuracy landmarks as a reference, and the subsequent successful delivery of a number of services have been used here to justify the accuracy specifications for service control, low bridge alarms, headway, and fleet management. Assuming a bus travelling at 15 miles per hour (6.7 m/s) at a tolerance of 5 seconds, the along track position accuracy for countdown (RTI) is specified at 30m (95%). For some applications, such as emergency management where communication with central control is available, it is assumed that the accuracy could be refined through radio communication. Furthermore, integrity requirement is driven in this case by a requirement for an operator to receive a call from a bus within 1.5 seconds. The availability requirement is specified here based on the data on radio communication availability of a period of four years, while the targets for the application is derived from Garage availability over a period 2.5 years. In the case of bus priority, the targets are based on a study on bus delay savings undertaken by Transport for London (in 2004. The main driver here is the requirement that the signal trigger time should not be in error by more than 1 second.

It can be seen that the required positioning accuracy ranges from 1m to 50m (95%) while the integrity risk requirement can be as low as 2.10^{-7} for some services. The required service continuity ranges from 99.5% to 99.9%. The required service availability is from 99.0% to 99.5%. Taking the example of collision avoidance in urban environments, delivering metre level accuracy with an integrity risk of 2.10^{-7}, 99.9% continuity of service and 99.5% availability of service, would present a considerable challenge. The next section proposes both functional and physical architectures for a positioning/location determination system that has the potential to meet the RNP.

3. POSITIONING SYSTEM ARCHITECTURE

3.1 Functional architecture

The current literature addresses the functional and physical architecture (e.g. Parker, 2008, Hounsell et al., 2012; Tilocca et al. 2017) at a very high level and do not explicitly account for the impact of applications, their required navigation performance and operational environment on the positioning architecture. Specifically, they do not delve into the details of integrity or quality monitoring, a key requirement for a mission critical operation such as bus service provision. In addition, there is no detail on the sensor integration concepts which are important for maximising the availability of bus location determination systems. Therefore, based on the LBS and their requirements determined in section 2, and the characteristics of the operational environment, Figure 2 presents a functional architecture for the bus positioning system. It accounts for the need for integrity monitoring of the positioning/navigation solution to support the mission critical applications. Furthermore, as bus positioning in built environments pose particular challenges in terms of attenuation and blockage of signals, the architecture is designed to improve the continuity and availability of positioning. Traditionally, this has been done by combining position solutions from different sensors and then generating a final position solution, referred to as position domain integration (Elhajj, 2017).

However, position domain integration is undesirable since for example, a GPS position solution is required before integration. In this case, when there are less than four satellites in good geometry for 4-D positioning, there would be no position fix from the GPS terminal relying instead on dead reckoning. This is exacerbated by the need for integrity monitoring, where measurement redundancy is required. Hence, position domain integration requires that the individual sensors generate enough measurements for positioning prior to integration (Groves, 2013). To address this, it is sensible to perform the integration at the measurements level, i.e. measurement domain integration, in which the measurements from the different sensors are combined or integrated to generate a position solution. The advantage of measurement domain integration over position domain integration is that it facilitates positioning when the individual sensors do not have an adequate number of measurements.

The features above are captured in Figure 2, in which the core sensor data capture function represents GNSS, while the augmentation data capture function represents alternative complementary systems such as dead reckoning or opportunistic sensors. The measurement domain integration function integrates the measurements from the core and augmentation sensors, and uses positioning aiding information (e.g. distance and direction) from the map matching function to generate position solutions together with the data required for integrity (quality) monitoring. The solutions that pass the integrity monitoring function tests are output as the final position of the bus. In the event that a hazardous measurement error is detected, the integrity monitoring function identifies it and passes the information back to the measurement domain integration function for a new position solution excluding the significantly erroneous measurement.

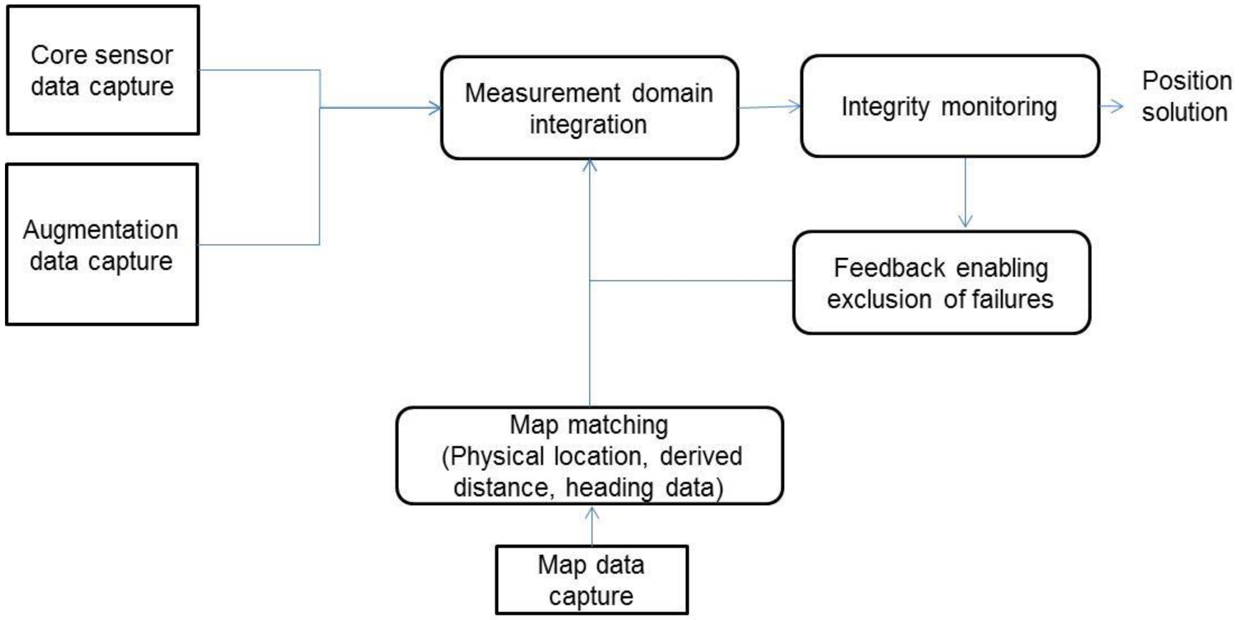

Figure 2: Bus positioning functional architecture

3.2 Physical architecture

There are a wide variety of technologies that could in principle be used to support the positioning/navigation module of bus operation systems including space based (GNSS and their augmentations), terrestrial systems (Dead Reckoning - DR, Wireless Local Area Networks–WLAN and Map Matching-MM) and space/based terrestrial augmentations (Elhajj, 2017). Taking into account the strengths and weaknesses of these technologies (e.g. GNSS – high accuracy but low availability in the urban environment; DR – low accuracy but high availability; WLAN – low to high accuracy and increasing prevalence of nodes/access points/transmitters), the complementary strengths are used to propose an architecture for urban bus operations (Figure 3) to implement the functions in Figure 2. The core of the system is multi-constellation and multi-frequency GNSS (metre level accuracy), strategically augmented with terrestrial signals of opportunity (SOOP), in particular decimeter level Wi-Fi based positioning (Nur et al., 2010; Nur et al., 2012). In addition DR using the odometer (displacement measurement, Δd) and low cost rate gyroscopes (change in direction, $\Delta\theta$), and in some cases aided by map derived data, can be useful in the event that there are failures with either the GNSS or opportunistic signals.

The multi-sensor fusion is undertaken in the measurement domain to maximize availability of the positioning solution in terms of the Easting and Northing coordinates (E, N), velocity (v) heading $(\theta)$and their uncertainties $(\sigma_N, \sigma_v, \sigma_\theta)$. Advanced map-matching algorithms (Quddus et al., 2007) should be used for link identification (*LinkID*) and physical location determination $(E_{LINK}, N_{LINK}, s_{mm})$. Integrity monitoring is performed both within the data fusion and map-matching functions. Note that there is a wide variety of integration algorithms such as basic and weighted averaging, consensus sensing, weighted least squares, kalman filtering (and its variations including its non-linear version referred to as the extended kalman filter), neural networks, fuzzy logic and particle filtering (Groves, 2013).

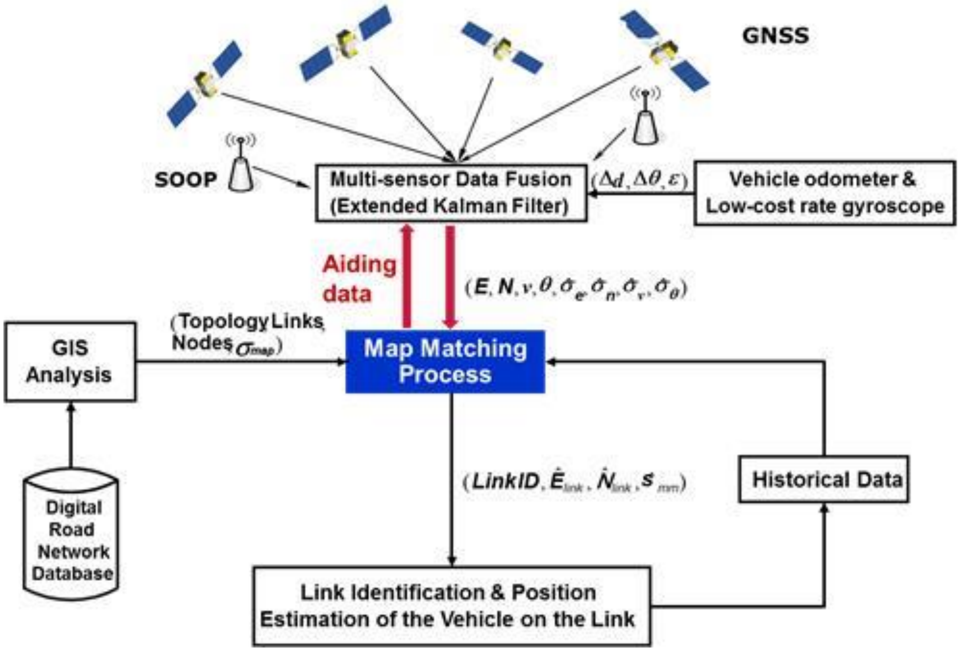

Figure 3: Proposed architecture for urban bus operations

Although significant research effort has been dedicated to aspects of the architecture in Figure 3 (Elhajj, 2017), there are many challenges that are still to be overcome. These challenges can be attributed to the RNP. In terms of accuracy, achieving metre level accuracy requires: (i) the use of the more precise but higher complexity ambiguous GNSS observable, the carrier phase, (ii) the adoption of multiple-frequency GNSS positioning capability exploiting advanced modernised and new signals, (iii) decimetre level positioning accuracy with SOOP with the potential to replace DR, and (iv) high resolution maps and advanced map-matching algorithms. In terms of integrity, multi-sensor integrity monitoring capabilities are still to be developed particularly for high accuracy positioning. On continuity and availability, intelligent context adaptive multi-sensor integration techniques are required to effectively realise positioning ubiquity in the urban environment. Finally, appropriate testing and validation techniques are required for very low percentile risk requirements, to support approvals and certification process.

4. CONCLUSIONS

The advantages of buses over private-vehicles dominated urban transport systems include less congestion, lower energy consumption and less emissions. Buses therefore, have the potential to be the most universal solution for sustainable urban travel from an economic, environmental and social aspects. This has spurred a speedy evolution in bus technology, infrastructure, concepts of operation, business models and operational best practice. In addition, significant effort is being expended on increasing the attractiveness and awareness of bus systems. A detailed literature review has been undertaken to capture the state-of-the-art in these aspects of bus operations (including actual implementation, and research and development). While the current initiatives including specific examples in Europe, have the potential to improve bus operations, none addresses in an exhaustive way, the significant operational element that relies on Location Based Services (LBS). This paper complements these initiative to increase operational efficiency recognising that this depends to a significant extent on the knowledge of the position and location of buses within the transport network. It is argued that neither the services nor their required navigation performance have been determined exhaustively and agreed universally. Hence, a comprehensive list of the location based services for urban bus operations have been determined and presented in this paper. The methodology adopted included a review of the relevant literature and a dedicated representative global survey of the main bus operators in eleven major cities. Furthermore, a process to quantify the required navigation performance for the services has been presented at a high level and the initial results presented. Based on the services and the initial RNP, a plausible positioning system's functional and physical architectures have been proposed, with distinctive features that address both the complexity of the urban bus operational environment and the level of criticality of the location based services. Research is ongoing to quantify the RNP and assess the impact of the proposed architectures on the RNP. The applications, their requirements and positioning system architecture are essential for the relevant stakeholders for the formulation of appropriate policies, regulation, service provision, and development and procurement of urban bus positioning systems.

Application / Service	User group	Along track Accuracy (m, 95%)	Cross track Accuracy (m, 95%)	Integrity			Continuity (%)	Availability (%)	Update Rate (UR)
				Alarm Limit (m)	Time-To-Alert (TTA) (s)	Integrity Risk			
Service control	Operators	12	15.00	20 / 25	<UR	1/round trip (100 min)	99.5	99.0	30 s or event
Countdown - RTI	Riders, travel/traffic managers, operators	30	15.00	50 / 25	<UR	1/round trip (100 min)	99.5	99.0	30 s or event
Bus priority	Travel/traffic managers and operators	6	15.00	10 / 25	2.0	1/round trip (100 min)	99.5	99.0	1 s
Low bridge alarms	Riders, drivers, traffic managers, operators	3	1.25	5 / 2	1.0	1/10years (bus) 1/year (network)	99.5	99.0	1 s
Headway	Operators, traffic managers	10	15.00	18 / 25	<UR	10^{-5}	99.5	99.0	30 s or event
Bus Lane enforcement	Traffic enforcement	12	1.40	2.45	1 (bus) or <UR	2.10^{-7}	99.9	99.5	1 s (bus) or 30s (operator)
Route guidance	Bus drivers, bus operators	10	12.00	18 / 20	2.0	10^{-4}	99.9	99.5	1 s

Table 6: Required navigation performance for urban bus LBS operations

Application / Service	User group	Along track Accuracy (m, 95%)	Cross track Accuracy (m, 95%)	Integrity			Continuity	Availability	Update Rate (UR)
				Alarm Limit (m)	Time-To-Alert (TTA) (s)	Integrity Risk			
Fleet management	Bus operators and managers	10	12.00	18 / 20	<UR	1/round trip (100 min)	99.9%	99.5	30 s or event
Intelligent Speed Assistance	Bus driver, bus operators /managers	10	1.40	20/2.45	2.0	2.10^{-7}	99.9%	99.5	1 s (bus) or 30s (operator)
Collision avoidance	Riders, operators, managers, asset owners	1	1.40	1.5 / 2.45	0.1	2.10^{-7}	99.9%	99.5	1 s (bus)
Emergency management	Operators, managers, fleet asset owners	50	1.40	80 / 2.45	1.0	10-3 – 10-6	99.9%	99.5	Event trigger
Lane Control	Bus drivers and operators	12	1.40	2.45	1.0	2.10^{-7}	99.9%	99.5	1 s (bus) or 30s (operator)
Restraint Deployment	Bus drivers and operators	1	1.80	1.5/3	<UR	10^{-5}	99.9%	99.5	1 s (bus) or 30s (operator)

Table 6: Required navigation performance for urban bus LBS operation

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