An Analysis of Systems-of-Systems Opportunities and Challenges Related to Mobility in Smart Cities

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***Abstract*—Urbanization is one of the major current trends in society. Cities around the world are looking into "smart" solutions based on information and communication technology to deal with the challenges that result from this development. Mobility is one of the most important areas to address, and system-of-systems solutions where vehicles and infrastructure are connected have a potential to improve urban transportation in many aspects. In this paper, current initiatives related to mobility in smart cities around the world are surveyed, and this is complemented with input from focus groups of transportation stakeholders to identify the important aspects of the problem. Based on this, challenges related to the application of systems-of-systems in urban mobility are identified.**

Keywords—systems-of-systems; smart cities; transportation; mobility.

I. INTRODUCTION

Urbanization is one of the major trends globally, and many challenges in the growing cities are related to transportation and mobility. Congestion, city sprawl, pollution, and scarcity of land are issues that many large cities face worldwide. Expectations are high on "smart" concepts such as setting up responsive services that balance demand and supply, offering citizens smart urban mobility through on-demand rather than fixed schedule public transit, or improving the distribution of goods in city networks using connectivity solutions and last-mile delivery robots and drones. Network effects such as cost reduction and increased convenience for citizens as well as reduced emissions are expected. In the long term, these mobility scenarios should be understood in a context where vehicles will become increasingly electrified; self-driving at an increasing number of locations and road conditions; and equipped with high-speed connectivity to off-board systems.

The future smart city can be described as an interconnected system-of-systems (SoS), where previously isolated systems get digitally connected to enable collaboration, thus forming a vast network open for multiple actors where new ways of offering services to citizens, businesses and entire cities become possible. The key characteristic of an SoS is that the constituent systems retain their independence, and are thus not tightly integrated into one unit, but they choose to voluntarily collaborate to achieve common advantages [1]. The aim of this paper is to improve the understanding of how SoS concepts can be applied to urban mobility problems.

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A. Context of Study

In Sweden, a long-standing program exists on strategic vehicle research and innovation, where actors from the automotive industry and society jointly fund and conduct research of about 1 billion Swedish crowns (SEK) per year. Previously, the focus of the program has been primarily on improving individual vehicles, but lately it has become increasingly clear that connected vehicles and infrastructure have a large potential in addressing urban mobility challenges. It is however only recently that an understanding has emerged that SoS engineering is a key to designing efficient solutions.

To investigate if this research program should refocus some of its resources on SoS for smart urban mobility, a pre-study was carried out during the Fall of 2017 by Research Institutes of Sweden (RISE), Volvo Cars, Volvo Group, Scania, and the Swedish Transport Administration. The paper summarizes some of the findings from that work.

B. Research Questions and Methods

This study addresses the following research questions:

1. What SoS-related solutions are currently applied in smart city mobility?
2. What aspects need to be considered when designing SoS-related solutions to urban mobility needs?
3. What opportunities and challenges exist when applying SoS to urban mobility?

The nature of the research is explorative, and therefore, suitable research methods are surveys of various sources, followed by a triangulation of the data. The study thus investigated existing smart city initiatives based on public data and complemented this with stakeholder focus group input.

C. Paper Overview

The remainder of the paper is structured as follows. In Section II, an overview is given of mobility applications in smart city initiatives around the world. Then, in Section III, important aspects related to the application of SoS to urban mobility are characterized. In Section IV, a number of opportunities and challenges related to SoS in smart urban mobility are identified. Section V relates this study to previous research, and in the final section, the conclusions are summarized together with indications of continued work.

II. Current Smart City Transportation Concepts

Some of the existing concepts for smart city transportation will now be discussed. As a basis, we use the definition of a smart city as one that uses "smart computing technologies to make the critical infrastructure components and services of a city – which include city administration, education, healthcare, public safety, real estate, transportation, and utilities – more intelligent, interconnected, and efficient" [2]. Here, "smart computing" refers to IT systems with real-time awareness and advanced analytics to help people make intelligent decisions.

Material for this background analysis has largely been collected from the web. Examples of document types are strategic documents from cities, third party evaluation reports of smart city initiatives, and media articles. Descriptions and evaluations of existing, established systems have been prioritized over concepts and pilots in this analysis since the main purpose was to paint a picture of the current situation.

A. Motivations for Smart Technology

The motivation for cities to become smart in the transportation domain is mainly to help them deal with growing amounts of traffic due to increasing population and number of vehicles. Congestion is a huge problem in most large cities on all continents, with loss of productivity and quality of life, as well as health and environmental problems as consequences. Cities are addressing this in two main ways:

- *Direct measures to decrease traffic*. By monitoring traffic flow to quickly detect problems city operations can redirect traffic, set traffic lights to shorter intervals etc. They can also inform residents about the current state of traffic to give them opportunities to take alternative routes or means of transportation (through services provided by the city or by third-parties such as Waze). Incentives to decrease the number of vehicles include taxes (Singapore), regulations restricting their use, and toll fees.
- *Indirect measures to make people use alternative transportation*. Improving public transportation (sometimes making it free), providing public bike rental systems (Paris), setting up charging stations for electric mopeds (Singapore), and building bike lanes (Copenhagen, Stockholm) are common options.

B. Smart Technology in Use

Singapore was one of the first cities to deploy smart technology for its transportation system, for example they implemented one of the world's first electronic road pricing systems. Since then, many cities have followed, and the range of smart technology for transportation has grown. Several tools or systems are quite common in cities today:

- *Road tolls*. Some cities, such as Singapore [3], have dynamic pricing that varies with the real-time level of congestion. Others have followed and, e.g., Stockholm has successfully reduced traffic by introducing tolls. Some cities also use the toll system as a data source for assessing traffic flow and level of congestion (Tainan).
- *Operations centers for traffic surveillance*. Many cities have installed centers to monitor and control the traffic based on various information sources such as toll systems, cameras (Rio, New York), and other sensors.
- *Public transportation services*. These are available for most cities and often include route planning for public transportation, real-time positioning of buses and the like, as well as information on congestion. Services are provided by the city (Singapore) or third parties.
- *Bike sharing*. Hangzhou in China features one of the world's largest system with over 65,000 bikes; Taipei and Paris are other examples.
- *Air quality monitoring*. Many cities are monitoring ozone, carbon dioxide, particles etc. in the air to be able to adjust traffic and inform the public.
- *Finding parking*. Available in, e.g., San Francisco, Singapore, Barcelona, and Tel Aviv, and contributes to decreases in circulation traffic and emissions.
- *Transit signal priority*. Buses equipped with sensors get priority to avoid delays (New York, Stockholm).
- *Smart trash cans*. Many cities have deployed trash cans that are solar powered, connected, and able to compress the garbage. This means that they contain more trash than regular cans and can notify central pickup when they need to be emptied to allow planning routes for emptying only trash cans that are full.

The list above describes quite mature systems that have spread to many cities. Thus, the difference between the cities working towards becoming smart is not that significant. There are very few examples of cutting edge technology in actual use, besides a few small-scale tests of autonomous vehicles.

C. Making Use of Data

Data and access to data is considered crucial for the smart city. Many projected opportunities build on access to large amounts of data, often in real time, from residents, vehicles, or other types of sensors around the city. As mentioned above, every city has a long way to go before this is a reality, but certain cities have taken significant steps along the way.

Amsterdam and San Francisco are examples of cities that have worked for several years on making data public for residents and third-party providers. In Amsterdam, the work on making data public has had the positive internal effect that the city has become more aware of its assets and challenges, since the separate parts of the city have had to coordinate and collaborate to provide data on the whole city.

On an application level, Amsterdam started to share traffic data with a commercial partner in 2015 [4], and thus got access to their processing algorithms to help alleviate congestion in the city. San Francisco provides more than 2,000 data sets in its portal datasf.org. One successful application is using data from sensors on parking spaces around the city. Several third-party developers provide apps that locate free parking space, which has significantly reduced traffic in the city center.

Even though there is a long way to go, small, isolated islands of the data-driven city are being put in place. There is a great opportunity to apply SoS principles to connect those isolated parts together to provide even more value.

III. Characteristics Of Smart Urban Mobility

Urban mobility is clearly a complex problem with many aspects. In order to characterize those aspects, direct feedback from a broad cross-section of stakeholders was needed. Therefore, three workshops were arranged as part of the study, in which a focus group method [5] was applied.

The first two events involved practitioners from industry and society, whereas the last one was with university students, to get the perspective of younger people. The number of participants were 25, 17, and 60 persons at the three events. The participants were divided into smaller groups of 4-5 persons that worked for a limited time on a specific question. These questions included: urban transportation needs; ecosystem and stakeholders; trends and context; solutions; information needs; and incentives for information sharing. The remainder of this section will summarize the workshop results.

A. City Mobility Challenges

The current trends in city development pull in two directions: one is that the centers are becoming *denser*, and one way to achieve this is to construct higher buildings that give more living and working space per unit of land. At the same time, cities are also *sprawling* so that the total land usage expands. This means that mobility needs are different across the city, and that multi-modal transportation is frequent.

Two major groups of challenges can be identified. The first group relates to the individual *primary transportation need*:

- *Efficiency*: The transportation should be as *fast* as possible, which means that the city needs to find ways to limit congestions and improve traffic flows. It should also be as *cheap* as possible, with a smooth *delivery*, at a time when the recipient is available, and preferably also coordinated with other deliveries.
- *Quality*: The transportation should be *predictable* with respect to arrival time, and it should be *transparent* so that stakeholders can monitor key parameters and feel secure that it is carried out effectively. It should also be *reliable* and *robust* with respect to disturbances, and flexible when it comes to changes in the needs. Finally, it should keep certain quality *properties*, which can be exemplified by temperature (people, food, etc.) and comfortability (people, fragile goods).

The second group relates to *side effects* on society:

- *Environment*: This includes both global environment, e.g. climate, and local, e.g. air quality and noise.
- *Safety*: Since transportation requires physical momentum, there is always a risk that the energy is accidentally damaging people or property, and this risk should be minimized. This relates both to the people being transported and to bystanders.
- *Resource usage*: *Land* is a scarce resource in cities, and it is desirable to minimize the usage for roads and parking. Another resource is *energy*. There are also the *public finances*, which should not be spent more than necessarily on transportation infrastructures.

Several of these aspects combined result in the overall *city attractiveness*, which is important in attracting inhabitants to live there and contribute to the society through taxes and in other ways. Aspects of this include to be able to move smoothly between parts of the city, while at the same time being affected as little as possible by other traffic, and to give priority to pedestrians. A similar aggregated characteristic is *livability*, which is often mentioned in strategic documents from cities and which is obviously important to inhabitants.

It should be noted that there are inherent conflicts between the needs described above, especially between the individual and societal interests. An optimal solution must thus find a reasonable trade-off between the diverse needs and objectives. Often, the city administration or similar has to be the actor that looks after the public interest.

SoS engineering provides an opportunity to handle this through its tools for understanding emergence as a result of the collaboration and finding suitable trade-offs between individual and societal needs.

B. Transportation Needs

City mobility obviously occurs because somebody has a need to move something. This need is independent of the kinds of vehicles used, and often a certain mobility need is fulfilled by a chain of transports of different modalities.

For *people* mobility, the following needs were identified:

- *Daily commuting* between homes and work or school.
- *Travel as part of work*, e.g. by craftsmen, home care, emergency services.
- *Rare traveling*, e.g. going to events.

For *goods* transportation, the generic needs are:

- *Groceries*: Delivered to households, shops and restaurants, and requiring timely delivery and controlled temperature to retain freshness.
- *Small goods*: Transported to households, as a result of e-commerce, but also to businesses.
- *Large goods*: Include material to industries, infrastructure and building construction, maintenance.
- *Waste removal*: This is a consequence of a prior goods delivery resulting in surplus packaging material, and thus relates to both households and businesses.

C. Modalities

Different modalities can be used for the above transportation needs. For people, these are primarily:

- *Non-motorized*, i.e. walking or bicycling.

- *Personal*, using a car or other smaller vehicle for a specific route and time, where the vehicle can be either private, from a car pool, or a taxi.
- *Public*, using bus, tram, subway, railway, or boat, where route and time is predefined by the operator.

For small goods, it is possible to use the same modalities as for people. For all goods, there are also options to use trucks, boats, or trains. Often, containers are used to handle larger amounts of goods that are moved together.

For multimodal transportations, *hubs* play a key role as the places where the vehicle or modality changes, and where different items that were moved together can go in different directions. Hubs also include a temporary storage, when waiting for the next step in the transportation chain. A parking lot is a kind of hub for private transportation.

D. Actors and Stakeholders

In relation to each transportation need, there are many actors and stakeholders involved. From studying a set of specific cases, the following generic actor categories emerged:

- *Beneficiaries of transportation*: People who wish to get transported; receivers or suppliers of goods.
- *Transportation service suppliers*: Vehicle owners; transportation operators; logistics companies; hubs.
- *Infrastructure suppliers*: Road administrations and transportation agencies; IT and communication suppliers; energy suppliers (electric, fossil); parking providers; insurance companies.
- *Vehicle suppliers*: The manufacturers of vehicles.
- *Mediators*: Logistics coordinators; service brokers and orchestrators; platforms for data sharing; aggregators.
- *Society*: City authorities; city planners; traffic control centers; regulators; property owners; neighbors; tax payers.

E. Information

To improve the realization of a certain transportation need using SoS, it is necessary to understand the information flows between actors. Three dimensions are important:

- *Temporality*: The information can represent the current state (*real-time data*); the *history*; or predict the *future*.
- *Multiplicity*: The information can be *specific* to one transportation or *aggregated* based on data from many.
- *Source*: The information can have various *sources*. For people, it can come from that person's *smartphone*, giving e.g. GPS position. For goods, *tags* that provide unique identity for an item can be used and relate that to specific information that is kept in a database (e.g., type of goods, weight, volume, level of hazard, origin, destination, position, carrier, etc.). The *vehicle* used for the transportation also contains useful data.

IV. Analysis of SoS Opportunities and Challenges

Based on the descriptions of current smart city initiatives and from the characterization of urban mobility, an analysis was performed to identify SoS related challenges. As a frame of reference for the analysis, a previously developed strategic agenda for SoS research was used [6]. It identifies several challenges for SoS in general, across a range of application areas, and these correspond closely also to those relevant in the urban mobility domain.

A. Complexity Management

Many application examples identified in Section II are quite small in scale and are developed and operated in isolation. However, there is a lack of knowledge how to connect different pieces together in an SoS. What would be a common basis, in terms of information infrastructure, communication protocols, etc. that would allow such connections? How would solutions scale as more and more applications and users are added? What is the distribution of responsibility across different stakeholders? These are key questions to address to manage the complexity of the SoS.

B. Socio-Technical Effects

Many of the smart city concepts seen so far are technology driven, and they are assuming that humans are adaptable. This could include the willingness of people to adjust their means, time, or route of transportation, as well as to share data. However, when moving from small-scale demonstrations to broader usage, it is often seen that people are less willing to adapt than the engineers have anticipated, and hence the effects are in reality small. Another difficulty involves the systemic consequences when people actually do adapt. This can lead to emergent dynamic effects that create new, and unforeseen issues. As an example, a successful information system that increases incentives to use public transportation could move the congestion problems from the roads to the subways.

C. Architecture and Interoperability

The overall architecture is always a key question in SoS, that clarifies issues like which elements are included; how they are connected; what the interfaces look like; what their roles are; and what information they exchange.

In SoS for urban mobility, one concern is whether there should be a central coordinator or mediator, and in that case what role it should play. In many cases, this mediator is needed for data sharing, aggregation, and levelling incentives.

Another question relates to how data from vehicles can be gathered by third-party services, and this is a topic where stakeholders have different interests. In Europe, the automobile manufacturers propose a fairly limiting solution [7], whereas the European Commission demands more openness [8].

To allow information flows, there is a need in the architecture for technical standards on various levels so that the systems can understand each other and to achieve interoperability. It is not likely that one single SoS solution will emerge for all transportation related needs in a city, and hence a system will often interact in several SoS simultaneously.

D. *Multi-Modal Transportation*

A theme that was recurring throughout the study was the need to improve multi-modal transportations, which basically requires coordination between several means of transport, thus requiring an SoS. The need largely stems from the dual nature of cities, namely the densifying centers where efficient public transportation is preferred due to land and energy usage, and the sprawling suburbs where cars are necessary as a complement. Many transports go between these sectors of the city and require a combination of transportation means.

E. *Data*

Data is what drives the smart city, and its handling in an SoS is thus fundamental. The main trend is to improve situational awareness through more sensors delivering more data, with the expectation that this data can be used to solve more problems. Over time, this leads to a data archive that can be used for modelling and evaluations. Central collection of data for short-term dynamic control of traffic flows as well as medium-term to long-term planning of infrastructure investments and maintenance is mentioned.

Open data is seen as important, as it gives hope that entrepreneurs can develop solutions beyond the imagination or capability of the city authorities. This leads to, in the future, more data sharing and more public-private partnerships, but there is a lack of understanding on how to organize this.

Some of the data is expected to come from user contributions through crowd sourcing, but this has several issues, such as data quality and sustainability, i.e., how to keep up people's interest in continuing to participate.

F. *Business Models and Incentives*

Most transportation services have an economic dimension, and the provision of a successful and sustainable service requires that all involved stakeholders in this business ecosystem have a positive cost-utility-balance. The business models of an SoS raise a number of issues, one of which is what payment models should be used for the data that is shared. Obviously, an actor that contributes data for others to use wants something in return, as is always the case in a sharing economy. The compensation could be monetary, but other options exist as well, such as offering services in return for data. Improved methods for SoS business analysis are thus needed, as suggested in [9].

As discussed above, an SoS often includes a mediator, data aggregator, or orchestrator, in the form of a central IT system. An important question is who will take responsibility for its development, operation and maintenance, and how they will be compensated for this. In some cases, it could be part of a service that clients pay for, and then it is natural that the service provider takes this role, whereas in other cases it could be seen as part of a societal infrastructure, that requires a public authority to take responsibility.

One motivation for publicly funded infrastructures could be that the SoS addresses some of the societal challenges related to urban mobility, as discussed above. This could also motivate other involvements from society in order to stimulate or discourage certain solutions. The range of control mechanisms that society has includes taxes, incentives, standards, and open data of value to others.

When creating an SoS, several actors invest in it, and the sustainability over time of a high-quality service becomes important to get a pay-off. Both legal and organizational arrangements may be necessary, including contracts. With this comes also questions of liability, should any party not fulfill its obligations, or cause damage to third parties, i.e., people or property not involved in the transportation.

G. *Trust*

Establishing trust in the SoS among its users is a must, since participation is largely voluntary. For the consumers, trust involves privacy and integrity, and here the new EU regulation GDPR [10] is an issue. It has positive effects in that it provides transparency towards users on how data is handled, with a clear ownership remaining with the user, which could increase willingness to join the SoS. On the other hand, there may be technical challenges related to fulfilling GDPR in an SoS, and ultimately some SoS may not be feasible.

Since information exchange in an SoS inevitably requires a certain degree of openness, cyber-security becomes an issue, to prevent unauthorized actors from accessing data or disturbing the operations of the SoS so that it cannot deliver its intended service, or even becomes unsafe.

H. *Engineering Methods*

There is a need to find efficient engineering methods for SoS. The particular challenges here, compared to traditional product-oriented systems engineering, are that SoS development is a collaboration among several actors; that the SoS will evolve over time, and hence make engineering more of a continuous activity; and the fact that the effectiveness of solutions will depend on complex dynamics involving behavioral changes among users. Modeling and simulation techniques are key enablers in SoS engineering. For urban mobility, a basis is traffic simulation, that allow the study of dynamic effects depending on how the SoS is designed.

V. Related Research

Due to the complexity of challenges associated with the smart city, there are several frameworks proposed to structure the understanding and harmonize the terminology. In [11], technological, human, and institutional factors are suggested as the fundamental components of a smart city, and integration of technological factors, learning for human factors, and governance of institutional factors as the strategic dimensions. Eight success factors for smart cities are listed in the integrative framework of [12]: management and organization; technology; governance; policy context; people and communities; economy; built infrastructure; and natural environment.

Applying an SoS approach to the smart city is not new. In [13], different challenges are identified for smart cities in general, i.e. not just the transportation system, and an SoS where citizens and government agencies interact is outlined. A summary of experiences from ten smart city initiatives is provided in [14].

Some of the IT challenges in smart cities are discussed in [15][16]. Internet of Things is generally considered a key technology in the smart city, which is discussed in [17][18], including its applications to infrastructure and buildings; transportation; energy; and healthcare.

The transportation system [19][20][21], or subsections of it such as the maritime transportation system [22], has previously been seen as an SoS. The aspects studied include optimization of traffic flows in mixed road networks using cooperative traffic control [23]. We add to this emerging body of research a bottom-up perspective on the variety of needs and challenges of future transportation systems. By taking the perspective of various stakeholders, we started to map out their respective transportation needs and along with that unfolding both potential conflicts in the transportation system and potential contributions and solutions from the SoS domain.

VI. Conclusions and Future Work

Many cities are tackling issues related to transportation, as they are growing. Smart solutions building on connected vehicles and infrastructure appear to be attractive approaches. Taking an SoS approach gives many opportunities that allow this to happen systematically on a larger scale.

However, as has been shown in this paper, implementation of such solutions in practice has only started, and many issues need to be resolved. The paper contributes by characterizing the many aspects that must be dealt with when engineering such solutions and provides an analysis of challenges to SoS in this domain. The main topics were complexity management; socio-technical effects; architecture and interoperability; multi-modal transportation; data; business models and incentives; trust; and engineering methods.

Based on the findings of this study, the strategic vehicle research and innovation program in Sweden has decided to launch an initiative on SoS for smart urban mobility. It will have a total budget of 100 MSEK, split evenly between industry and government agencies. The duration is 2018-2021 and it will consist of a portfolio of R&D projects that focus on specific SoS-based applications in urban transportation. This is complemented by a core activity focusing on building joint knowledge on SoS engineering in this area.

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