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Smart city platform adoption for C-V2X services

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Abstract

Successful adoption of urban cellular vehicle-to-everything (C-V2X) services by consumers requires high-density network coverage and a diverse and vibrant community of service providers. This work analyses the economic and technological requirements for a successful smart city platform adoption for such services by modelling the interaction of different sides of the platform and related network effects by means of system dynamics.

This work suggests that the adoption of such a platform is a long-term process. Its success depends on the ability of stakeholders (i.e., operators, service providers, the city, etc.) to collaborate in achieving data compatibility, allowing its sharing and efficient usage, which in turn increases the quality of the offered services and accelerates consumer adoption. In addition, this study suggests some pricing and investment strategies which may be helpful for a successful deployment of such a platform.

Overall, a smart city platform for C-V2X services involves high uncertainty; however, it may potentially create new sources of large societal benefits.

Keywords: smart city, connectivity and data platform, connected vehicles, adoption, critical mass, network effect, low latency and ultra-reliable requirements, system dynamics.

1. Introduction

The fifth generation of cellular technology may not only enhance the current mobile Internet but also connect new objects to a digital platform, thus digitalising local economic activities and creating opportunities for new business models and welfare sources. It is generally accepted that connected cars have high potential since they affect society at large and may enable a wide variety of use cases. However, the adoption of a platform, including such services faces high uncertainty. The wide range of possible services makes it difficult to forecast demand and complicates the prioritisation over technical requirements, including 5G metropolitan networks. This work studies the case of connected vehicles as the main use case driving new service generation and investment.

A smart city platform for connected vehicles can enable a wide variety of new services, including infotainment, navigation, safety, insurance, and positioning services via cellular vehicle-to-everything (C-V2X) connections. Example services are real-time situation awareness, intersection movement assistance, vulnerable road user discovery, a dynamic reserved lane for emergency vehicles, autonomous vehicle parking and remote driving. In addition, some C-V2X services may require low-latency connections to be provided via mobile edge computing and network slicing (Shah, Ahmed, Imran & Zeadally, 2018), which needs to invest in highly dense 5G infrastructure.

Like any other multi-sided platform, a smart city platform presents network effects and critical mass due to the interaction of multiple types of users (Rochet & Tirole, 2003). Connected vehicles require a dense 5G metropolitan network and a critical mass of service providers. Service providers require a critical mass

of connected vehicles and 5G network coverage, including new technology requirements such as mobile edge computing and network slicing for achieving low latency and ultra-high reliability. Finally, the platform manager requires all sides to reach critical mass (connected vehicles and service providers) to be able to recover the investment. Thus, the successful adoption of C-V2X services needs to analyse the dynamics of critical mass of each side of the platform, together with the related network effects.

Due to network effect, a successful adoption may depend on two crucial platform resources: the network coverage and the availability and quality of data (Basaure et al., 2019; Mitomo, 2017). Hence, the platform manager should play an active role in the development and operation of both the 5G network and the data resources (Benseny, Walia, Hämmäinen & Salmelin, 2019). This work aims at analysing the dynamics of the adoption of C-V2X services from the perspective of the platform manager controlling both network and data platform to enable a wide supply of services with different technical requirements. In other words, it aims at answering to the following question: which platform requirements enable adoption of C-V2X services?

2. Background

2.1 5G smart city solutions

Cities around the world are adopting Information and Communication Technologies (ICT) to digitalise internal processes and monitor the urban environment, aiming to become more efficient and to enable new digital services. First smart city projects deployed sensor networks throughout city streets to improve information on public transport, remotely control streetlights, and monitor a wide range of magnitudes, such as air quality, parking spaces, waste bins, etc. Most of these sensor networks employed IEEE-based wireless technologies since 3GPP LTE networks primarily supported broadband and lacked the flexibility to address low-battery, low-activity requirements.

However, 5G mobile technologies support Massive Internet of the Things devices (MIoT), thus becoming a potential substitute for the existing IEEE-based sensor networks. In addition, they improve existing broadband capabilities via enhanced Mobile Broadband (eMBB), and they will support a new type of communication, i.e., the Ultra-Reliable Low-Latency Communication (URLLC). Therefore, new 5G-based smart city solutions are being developed, promising to enable a broader range of applications than before. Although 5G services may initially be provided via existing macro cell sites, the exploitation of mmW bands, e.g., 26 GHz, requires the deployment of smaller cells with a few hundred meters coverage.

Network equipment vendors are developing new smart city products that integrate sensors, 5G antennas, and other equipment into street furniture, e.g., light poles, bus stops, kiosks, etc. For example, Nokia is developing a 5G smart light pole that can incorporate LED lights, 26 GHz mobile antennas, multiple video cameras, air quality sensors, information displays, electric vehicle charging, drone landing stations, and RTK-based positioning base stations (Landertshamer et al., 2019). The deployment of 5G smart light poles can facilitate the massive deployment of 5G small cells and sensor networks while addressing cities' aesthetic requirements.

5G smart city systems can be deployed following different structures, affecting the connection latency and reliability as well as the deployment cost. Alternative deployment structures can differ in the location of edge computing resources and baseband processing, as shown in Figure 1.

5G allows centralising some Radio Access Network (RAN) functions, aiming to reuse computing for the baseband processing of multiple Remote Radio Heads (RRHs). In Figure 1, deployment options 1 and 2 follow a centralised RAN (C-RAN) architecture, potentially reducing deployment cost. However, C-RAN architectures can require high bitrates between the RRH and the newly centralised baseband, depending

on the degree of function centralisation (i.e., higher-/lower-layer splits between control and user plane). For example, two antenna ports on a system with a frequency bandwidth of 200 MHz can demand maximum rates of 20 Gbps, possibly requiring a street-level fibre network (3GPP, 2017).

5G smart city solutions typically support edge computing, enabling steering of traffic towards local hosting locations (i.e., local area data networks) instead of tunnelling it directly to the telco cloud. Thus, smart city applications (e.g., smart traffic control, remote driving services) can be located within the city borders and closer to end devices, reducing end-to-end latency. In Figure 1, in the deployment option 2, the edge computing is located at the city level, enabling resource reuse for edge applications and baseband processing, reducing deployment cost. In contrast, the deployment option 3 can provide lower latencies but it may require higher deployment costs.

In addition, connection reliability via data redundancy can be provided to some extent, via 5G dual connectivity or multi-connectivity⁴ (3GPP, 2020). Some multi-connectivity implementations may be facilitated by dense small cell networks that follow a C-RAN architecture since the baseband processing of antennas providing redundancy may occur in the same local hosting, as in the deployment option 2.

We suggest that the deployment option 2 provides the best balance between deployment costs and connection latency and reliability. In addition, generic data management services can also be placed in the local hosting to allow storage, aggregation, and analytics of sensor-data, albeit these data services, are not standardised by the 3GPP.

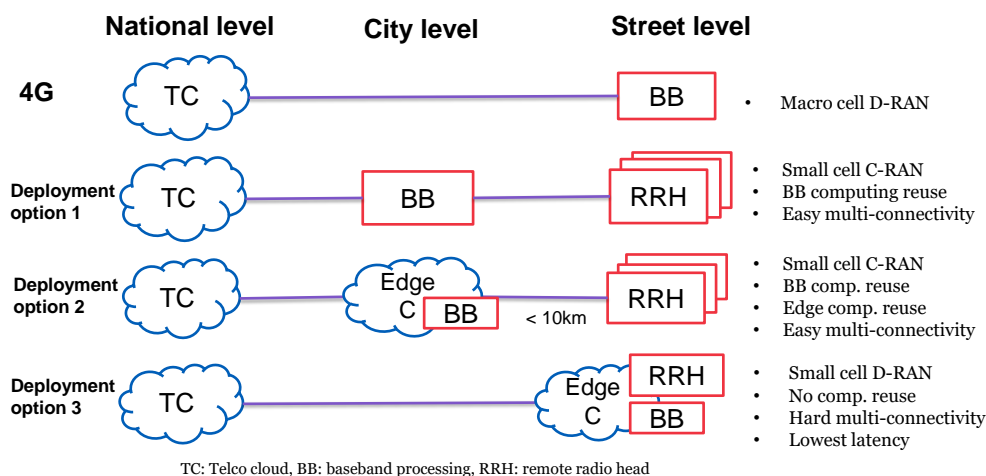


Figure 1: Alternative 5G deployment structures for the smart city

Therefore, 5G-enabled smart cities can facilitate C-V2X services, given that RSUs can be deployed alongside small cells, services and data can be locally managed via edge computing, and 5G URLLC enables more advanced services such as remote driving¹. In addition, small cells may be operated by a single actor, e.g. a neutral host operator, who can organise infrastructure sharing for incumbents or new players (Benseny, Walia, Hämmäinen & Salmelin, 2019).

2.2 C-V2X applications and technologies

Vehicle-to-everything (V2X) technologies enable communication between vehicles and the network (V2N), and other road entities, such as road infrastructure (V2I), pedestrians (V2P), cyclists and other vehicles (V2V). Two competing V2X technologies exist, including the Dedicated Short Range Communication (DSRC) and the Cellular V2X (C-V2X). Both technologies support direct

¹ 5G needs to be fully deployed on its non-standalone version for all URLLC-based services to be possible because the core network may require handling of network slices with different service requirements (3GPP, 2020).

communication between road entities using high-level protocol semantics from the ETSI Intelligent Transport System G5 standard (ITS-G5) via the 5.9 GHz band², designated as ITS frequency in many countries. However, they differ in the used radio communication technology, employing IEEE 802.11p and 3GPP 4G/5G, respectively. Another critical difference is that, in addition to direct communication, C-V2X also supports network-based communication via licensed spectrum, enabling interoperability with MNO networks (GSMA, 2017).

C-V2X supports both direct and network-based communications. Hence, it can address a broader range of service requirements, combine the deployment of Road Side Units (RSU) with 5G small cells, remain compatible with future mobile technologies³, and leverage the existing mobile ecosystem for extended business models⁴.

C-V2X services are under standardisation and development, aiming to improve road safety, traffic efficiency, and fuel consumption, among others. Services running on direct communication can enjoy reduced complexity, avoiding handover interruptions, and network authentication. Services include warnings on close-proximity hazards, such as roadblocks, traffic jams, and cyclists/cars behind a blind curve/intersection. These warnings can be used to assist drivers when turning, passing, and sudden braking, avoiding collisions. In contrast, services running on network-based communication can enjoy secure authentication and subscription-based payment options. These are suitable for automaker telematics, infotainment and navigation, informational safety (e.g., traffic queue warning, road hazard warning 1km ahead), fleet management, logistics, vehicle-as-a-sensor, and remote driving (e.g., teleoperated support for heavy machinery, support for remote driving of autonomous vehicles) (3GPP, 2018a; Ericsson, 2019; Qualcomm, 2017).

A critical technological enabler for C-V2X services is the Local Dynamic Map (LDM) and the Sensor and state map sharing (SSMS). The LDM is a local data repository that keeps updated information on both moving and stationary devices. Information is gathered from a variety of sources, including vehicles, infrastructure units, traffic control centres, etc. through a secure communication interface (ETSI, 2011). The SSMS is an extension of the LDM, to build a collective situational awareness with higher spatiotemporal fidelity. In addition, it enables low latency communication for precision positioning and control (3GPP, 2018b).

Advanced C-V2X services with demanding requirements on throughput, latency, positioning, and reliability will be gradually enabled as 5G mobile networks are deployed. The C-V2X development roadmap includes three stages. On the Basic Safety stage, based on 3GPP Release 14, communication exists in direct mode only via broadcast with no support for positioning or high speed/density vehicle scenarios. On the Enhanced Safety stage, based on Release 14 and 15, communication remains in broadcast mode, but support for high speed/density vehicle scenarios is enabled. Some degree of reliability, as well as position accuracy (< 1 meter), is available. Finally, in the Advanced Safety stage, which is based on Release 16 and therefore can benefit from 5G New Radio, unicast and multicast communication is possible with ultra-high reliability, ultra-low latency as well as ultra-precise positioning (<< 1 meter) (Qualcomm, 2017).

² C-V2X and 802.11p can co-exist in the 5.9 GHz since just 10MHz is required to support basic safety services, while 70MHz could support advanced safety services e.g., sharing data from on-vehicle sensors.

³ In the C-V2X architecture, direct communication happens over the PC5 interface, which was originally introduced in the mobile architecture for public safety cases e.g., during network blackout. For network-based communications, base station and vehicles employ the same technical interface used by smartphones, named Uu (3GPP, 2018b, 2018c).

⁴ Since both direct and network-based communications are defined by the same standard, they may be easily integrated in the same chipset, facilitating commercialization to more devices/users e.g., smartphones, cyclists, leading to a wider range of business models.

Road and regulatory authorities in many countries, including the US and the EU, are introducing mandates for automakers to include V2X technologies in vehicles. Currently, pre-commercial C-V2X deployments are conducted by multiple automakers.

2.3 C-V2X services as a multi-sided platform

The implementation of C-V2X services requires a platform since they connect consumer vehicles with multiple service providers. There are several definitions of platforms. Platforms may be understood as a transaction place (Rochet and Tirole, 2003), enabled by a modular architecture (Baldwin and Woodard, 2009) which defines a set of standardised components supporting the innovation and evolution of a system and at the same time constraining the linkages between components and platform. In such a platform, different interacting agents should be interoperable at different layers, so they are able to perform transactions and interact.

The analysed platform facilitating C-V2X services has two main components. The first one is the network infrastructure, which includes 5G antennas, different types of sensors present in vehicles and street infrastructure communicating with the network, and other network elements and functionalities such as mobile edge computing and network slicing. The second component is the data gathered by the platform coming from consumer vehicles, service providers and other sensors present in the street level infrastructure. The platform should assure interoperability between involved players at these two levels: physical infrastructure and data. At the infrastructure level, 3GPP provides standardised 5G communication, including sensors present in vehicles and street infrastructure. At the data level, the value of the information increases with its usage, combination and accuracy. At the same time, it decreases with time (Moody & Walsh, 2002), and therefore such data platform requires different stakeholders to cooperate to enable data compatibility and transferability to provide value-added services.

2.4 Network effects and platform adoption

By mediating the interaction between consumer vehicles and service providers, a platform for C-V2X services enables the adoption of the involved sides. By attracting different types of users, the platform generates networks of users, which are being drawn by the other users of the platform. This widely-known phenomenon called network effect is characterised by a critical mass of users, after which the adoption reaches an equilibrium of success. In the case of a digital platform, such effect is typically indirect, meaning that the value is coming for those users having a different role. In fact, Rochet and Tirole (2003) suggest that many markets exhibiting network effect behaves as a two-sided platform. Furthermore, with the emergence of IoT applications, platforms are becoming multi-sided (Porter & Heppelmann, 2014) and as they are enabling new ecosystems consisting of different types of users.

The adoption of technology has been successfully described by the Bass model. It was first used to explain the adoption of durables (TV in the case of the original article of Bass, 1969), and later expanded to a wide variety of networked products and services, such as telephony and Internet services (Kim & Kim, 2007), operating systems (Tseng, Liu & Wu, 2014), vehicles (Massiani & Gohs, 2015), etc. The Bass model describes the technology adoption as an S-curve, which may be explained by the existence of network effect and critical mass (Swann, 2002; Evans & Schmalensee, 2010). In fact, networked products and services (e.g. ICT) have reported experiencing a lower initial adoption rate and a higher one when the critical mass has been achieved as compared with non-networked products (Lee, Trimi & Kim, 2013). This means that a strong network effect makes the adoption to have a sharper S-curve which in practice requires more effort.

Besides traditional network effect, the emergence of data platforms has evidenced the existence of a network effect due to data (Mitomo, 2017; Schaefer & Sapi, 2019), which adds an additional requirement to critical mass.

3. Method and model

3.1 Methodology

This work utilises system dynamics to model the interaction of the multiple sides of the platform. System dynamics enables the wholistic analysis of systems (i.e., from a top-down perspective), including its dynamics and changes over time. It is especially suitable for analysing the adoption dynamics of platforms since it describes the interaction between different types of users in its overall effect in the system by employing feedback loops. Previous works utilising system dynamics for analysing two or multi-sided platforms are, among others, Casey & Töyli (2012), De Marco, Giannantonio & Zenezini (2015) and Ruutu, Casey & Kotovirta (2017). In this work, we model C-V2X services as a multi-sided platform to evaluate its requirements, including both economic and technical aspects.

3.2 Model

The model describes a platform enabling C-V2X services which mediate the interaction between consumers and multiple types of services providers, as described in Table 1:

Table 1 Platform sides

Platform actor	Role in the platform
Consumers	Connect to the platform and the 5G network through a privately-owned vehicle.
Basic service providers	Utilize the street level 5G connectivity with lower latency communications to provide safety and positioning services e.g. intersection safety systems, hazard alarm and assistance, Local Dynamic Map (LDM) service for precise positioning
Advanced service providers	Utilize the street level 5G connectivity with ultra-reliable and low-latency communications to provide advanced safety and extremely accurate positing services e.g. collective situation awareness, remote driving for autonomous driving, sensor and state map sharing for ultra-precise positioning
Data-based service providers	Utilize the information generated by connected vehicles and other service providers to generate new service offering e.g. insurance companies can provide usage-based insurance to connected vehicles, car manufacturing and monitoring services, municipalities can also optimize their resources (parking and security services).

Given the above-mentioned sides of the platform, two network effects are identified, as depicted in Figure 2:

- a) User /service level indirect network effect: the obtained benefits of each user are proportional to the number of users on the other sides of the platform.
 1. Connected vehicles to basic SPs
 2. Connected vehicles to advanced SPs
 3. Connected vehicles to data-based SPs
 4. Basic SPs to connected vehicles with basic subscription
 5. Advanced SPs to connected vehicles with advanced subscription
 6. Data-based SPs to all type of connected cars (basic and advanced subscription)

- b) Data network effect: the obtained benefits of each user are proportional to the amount of data from the users on the other sides of the platform. The value of data may increase with its quantity and quality. When the amount of data becomes larger, its value may also increase until a certain threshold. Also, the quality and value of the data may increase with its accuracy and

with the combination with other sources of data. Finally, its value may decrease with time because it becomes obsolete (Moody and Walsh, 2002). The related network effects are as follows:

1. Data generated by connected vehicles, positively affects the development of basic, advanced and data-based service providers
2. Data generated by SPs (basic and advanced), positively affects the development of data-based SPs, it improves the quality of the service offer and it accelerates the consumer vehicle adoption.

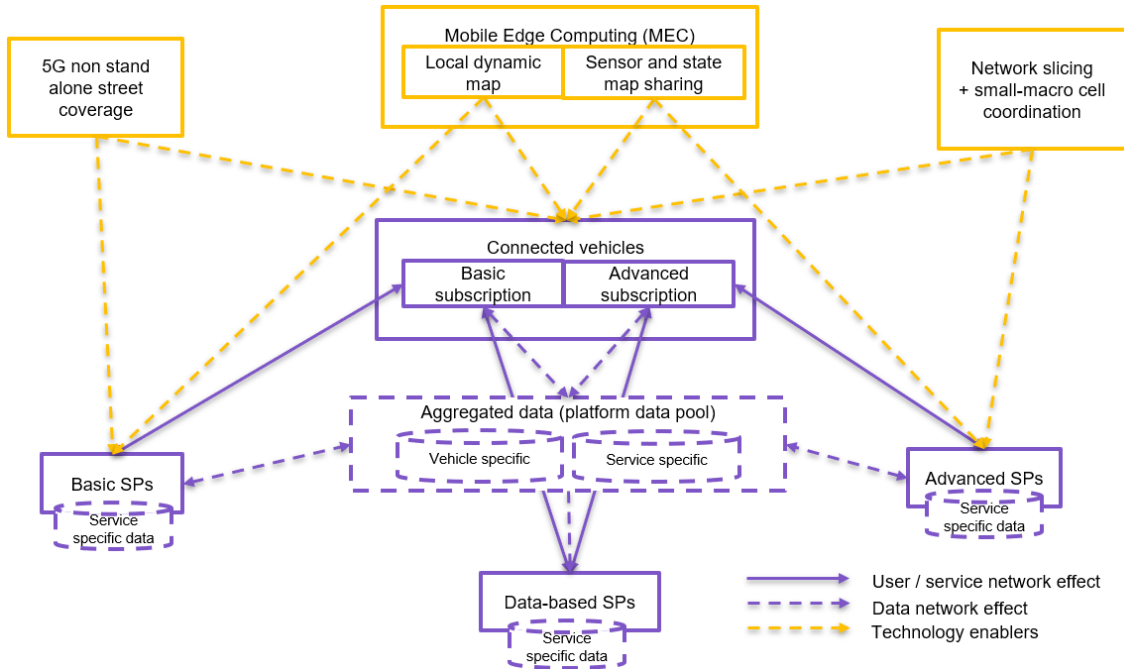


Figure 2: relation between different groups of users including network effects and technology enablers

The analysed platform deploys a data pooling business model in which vehicle and service-specific data is made available for other platform participants in exchange for a fee, as shown in Figure 2. On top of this, each service provider builds its service offering by combining with additional information coming from their own sensors and external sources.

Depending on the type of service, the criticality of the data may change. In general, the data coming from vehicles is relevant for both vehicles and service providers. Basic services demand real-time data to provide consumers with positioning and information services. For service providers, the historical data is also useful for developing their services and achieve higher accuracy and QoS. For other services such as monitoring and maintenance, updated historical data is equally valuable for consumers and service providers. For advanced services, such as advanced positioning services and remote driving, the consumers require highly accurate real-time data, while service providers also utilise historical data to develop their services. Finally, for data-based services, both current and historical data are valuable for both consumers and service providers. Real-time data may be related with user network effect, while historical data may be related to data network effect, since historic data increase its value through its enlargement (quantity) and enrichment (quality), both affecting the quality of the provided service. The value from data is summarised in the following Table 2.

Table 2: Value of data for different types of services and platform users

Type of service	Example of service	Value for consumer	Value for service provider
Basic services	Positioning and information services	Real-time data from vehicles and other complementary data from SPs	Real-time and historical data from vehicles. Complementary data from SPs
	Monitoring and maintenance	Updated historical data from vehicles (no real time critical)	
Advanced services	Advance positioning and remote driving	Real-time data from vehicles and other complementary data from SPs	Real-time and historical data from vehicles. Complementary data from SPs
Data - based services	Data based services (such as insurance)	Updated historical data from vehicles (from other SPs)	

Besides network effects, the adoption is positively affected by the availability of technology drivers:

- 5G standalone coverage: refers to the availability of small cells 5G antennas in the streets to connect vehicles with basic and advances services.
- Mobile edge computing (MEC): the availability of cloud computing at a city level (edge) facilitates services with low latency requirements, such as LDM and SSMS.
- Network slicing and small cell-macro cellular coordination: network slicing facilitates dealing with different QoS requirements and together with an improved small-macro cell coordination achieve both lower latency and high reliability requirements to provide advanced services.

Figure 3 describes the time evolution of connected cars and the effect on critical masses of the platform.

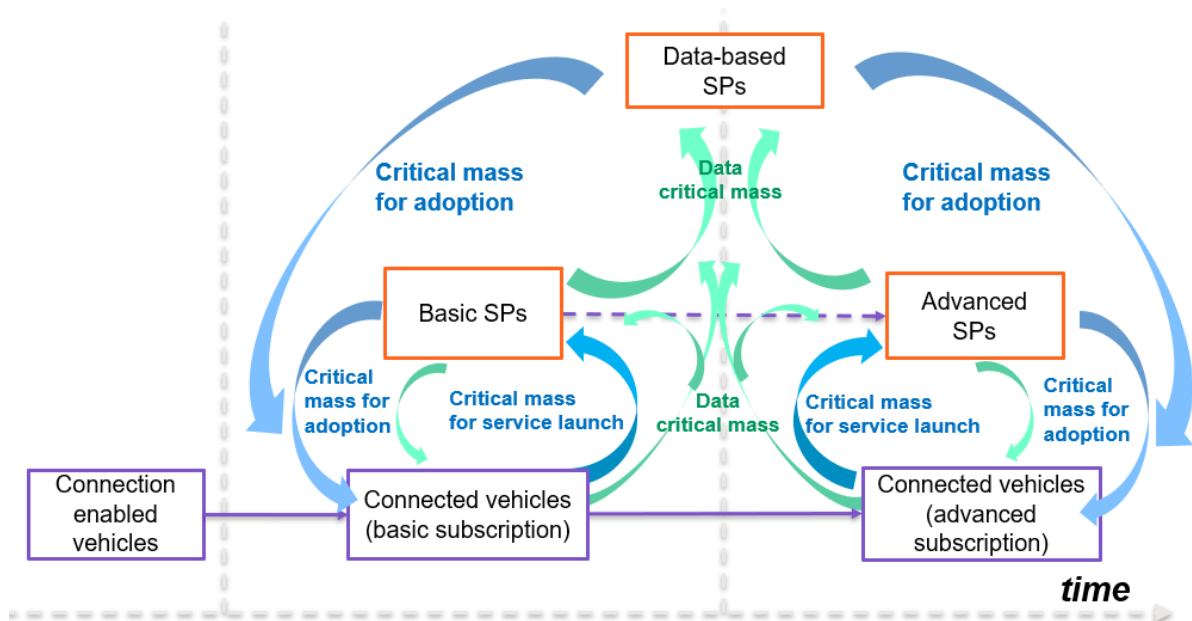


Figure 3: evolution of connected cars and relation and service providers and related critical masses

3.2.1 Consumer Vehicles

Vehicles are being gradually connected to the Internet. About 30-40% of vehicles are reported to be using some Internet service in more advanced markets (Statista, 2019a, 2019b). The model assumes an initial amount of consumer vehicles already connected via a wide area network (i.e. 4G) and that newly bought vehicles are connection enabled by default. Consumers take the decision on whether to connect to a smart city platform providing basic, advanced and data-based services depending on the type of subscription. A consumer should first connect to a basic service subscription to decide on the next level of subscription (advanced services). At any stage, and depending on the contract terms, the consumer may decide not to continue the subscription to the platform. If the vehicle is connected to advanced services and decide not to continue with such services, it will by default, continue with basic services until the next decision point.

The consumer adoption process is modelled by two consecutive Bass models, the first describing the decision of joining a basic subscription of services provided through a small cell 5G network and a second describing the decision of joining an advanced subscription (Figure 4). The innovation and imitation coefficients are those equivalent to an IP based application (Kim & Kim, 2007), as described in Table 3. On top of that, network effects impact the *word of mouth* adoption. The following system dynamics diagram consists of four stock of vehicles: non connected vehicles (without any Internet access), connection enabled vehicles (which are connection enabled and are connected by default to a wide area network), connected vehicles with basic subscription (which are connected to a small cell 5G network having access to more basic services) and connected vehicles with advanced subscription (which have access to more advanced services through a 5G small cell network). Both subscriptions have a predefined length (and related pricing rules) after which the connected vehicle consumer may decide whether to continue with such subscription. Vehicles become connection enabled at a constant rate, assuming that all new vehicles are equipped with cellular capability.

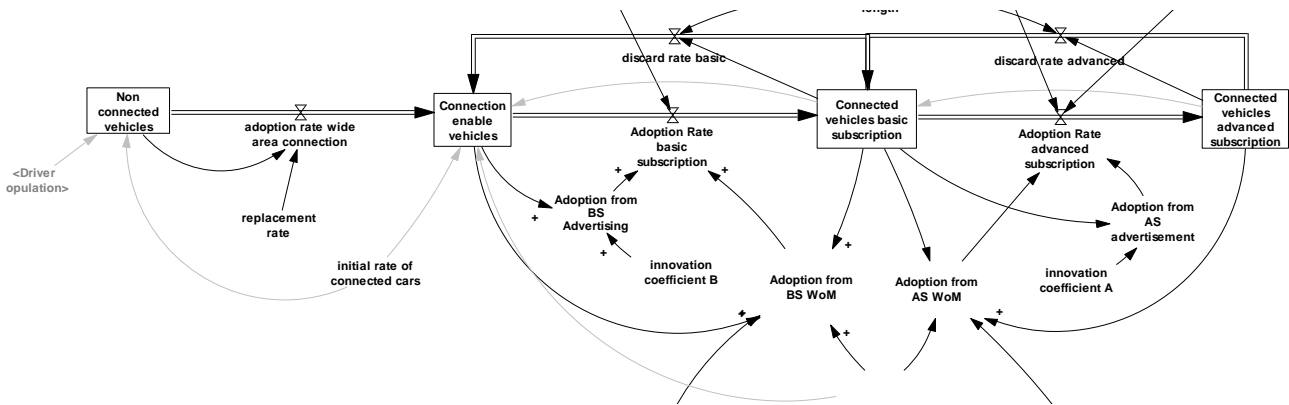


Figure 4: system dynamic representation of the evolution of connected cars

Table 3: Innovation and imitation coefficients of different sides of the platform

	Connected vehicles, basic subscription	Connected vehicles, advanced subscription	Service provider, basic	Service provider, advanced	Data based Service provider
P (innovation)	0.06	0.06	0.025	0.025	0.025
Q (imitation)	1.9	1.9	0.34	0.34	0.34

3.2.2 Service providers

The platform adoption by each type of service provider is modelled by a separate Bass model. The innovation and imitation coefficients are those equivalent to the diffusion of other application or service providers (Tsai & Hung, 2014) and considered to be the same for different types of service providers (Table 3). Since joining the platform requires service providers to invest, the model assumes that only after the payback time (service life cycle variable in the model) the service provider may consider the possibility of quitting the platform since such investment acts as a sunk cost and an exit barrier.

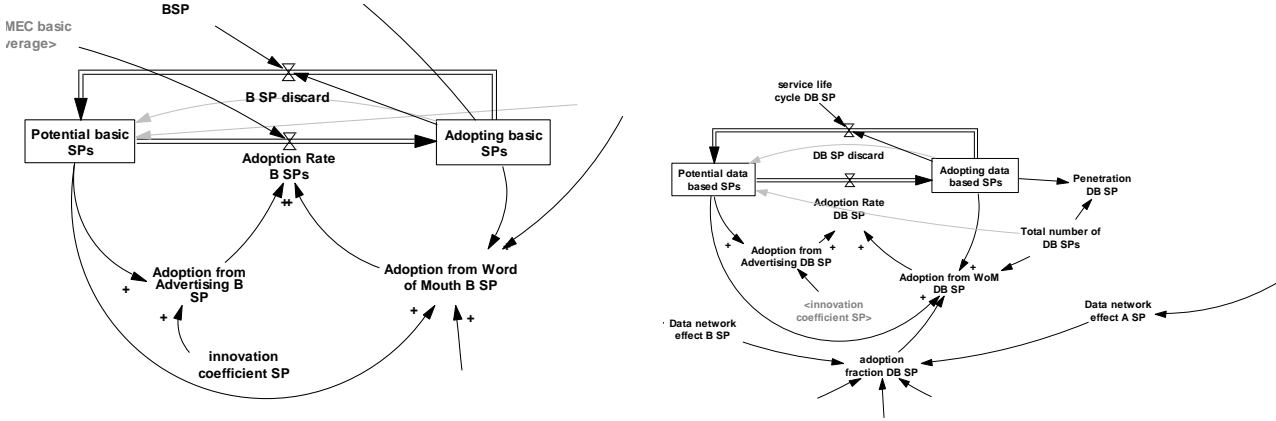


Figure 5: system dynamic representation of service provider adoption: (left) basic SP, (right) data-based SP

3.2.3 Network effect

The network effect describes the interaction between the different sides of the platform at service and data levels. The network effect is described herein as a negative exponential function as follows:

$$Eq.1 \text{ Network effect} = \frac{1}{1+a e^{-bx}}$$

, where x: number of users on the side(s) providing value, a, b: parameters defining the shape of the curve.

Since this is a general formula, it can equally describe the network effect experienced by consumers and service providers. In addition to the market penetration of the other side(s) of the platform, the infrastructure coverage and quality of the offered service enable to achieve a critical mass of users and therefore may be modelled as affecting the strength of network effect.

$$Eq.2 \text{ Network effect} = \frac{1}{1+ \frac{a e^{-bx}}{QoS}}$$

, where QoS: is a parameter from 0 to 1 describing the impact of infrastructure coverage and other factors impacting the quality of the provided services, such as data network effect. QoS is then defined as the minimum of factors producing the quality bottleneck to the whole system.

$$Eq.3 \text{ QoS} = \text{MIN} (\text{value of infrastructure coverage, data network effect})$$

The data network effect is modelled by evaluating the accumulation of data in the platform in time (from service providers and vehicles separately).

$$Eq.4 \text{ Data network effect} = \int_{t-c}^t (\text{value of data inflow} - \text{value of data outflow}) = \text{value of data market penetration dt}$$

, where *value of data* is a function which gives a value from 0 to 1 to the accumulation of data at certain time t , and c is the caducity time of data (i.e. after which data is not useful anymore for generating value). Figure 6 shows the general form of the network effect affected by the number of users on the other side of the platform and the provided QoS with its corresponding system dynamics representation. This figure describes the interplay between user and data network effects. It implies that fewer service providers are needed to reach the same level of consumer value if the utilisation of data improves. This is true because a better data utilisation means that service providers are able to improve their applications, increasing the perceived QoS by consumers (e.g. 100% QoS and 0.4 of service provider market share gives a similar network effect value than a 20% QoS and 0.6 of service provider market share).

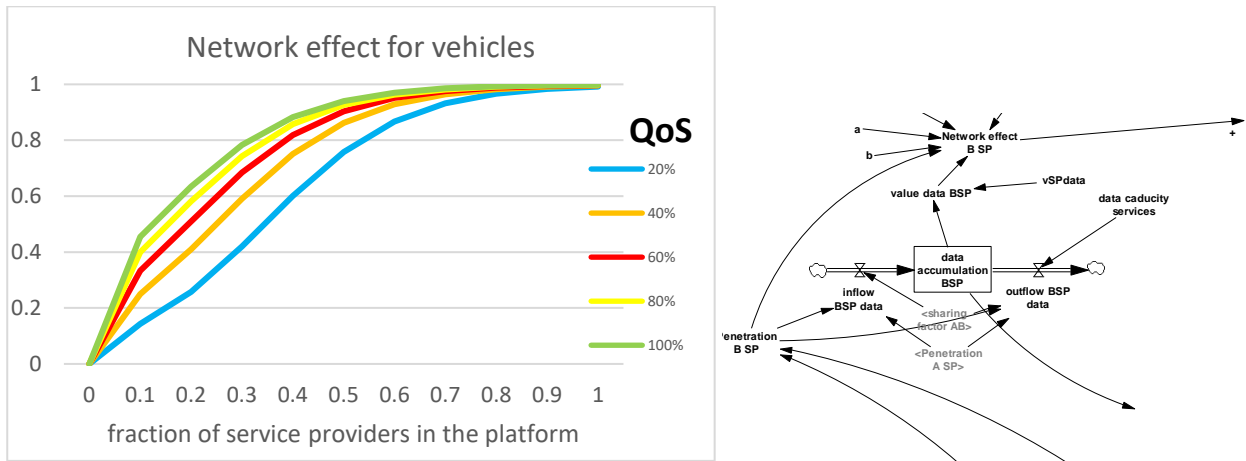


Figure 6: (left) Network effect for vehicles given a fraction of service providers and a certain level of QoS, with $a=2,5$; $b=-7,34$, and QoS from 20% to 100%. (Right) System dynamics representation of overall network effect

3.2.4 Technical architecture, system dimensioning, and cost model

We select a 5G smart city solution based on smart light poles. For simplicity, the model assumes the solution to include two types of poles with different hardware configurations, i.e., the street poles and the intersection poles. The street poles are equipped with a 26 GHz 5G radio. The intersection poles additionally include three daylight cameras, two infrared cameras, and two radars.

The selected solution follows a deployment structure in which baseband processing and application edge computing are co-located in a few city-level hosting locations, as shown in Figure 7. This deployment structure corresponds with the deployment option 2 described in section 2.2, providing a comparatively better compromise between deployment costs and connection latency and reliability.

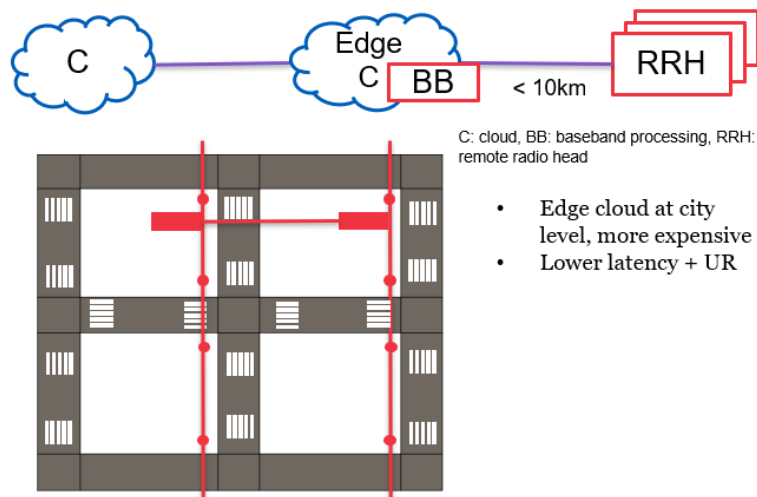


Figure 7: (up) Selected deployment structure. (down) Deployment layout of 5G urban network

The model dimensions the 26 GHz small-cell network by assuming an average throughput requirement of 50 Mbps and 100 Mbps per car for basic and advanced services, respectively (3GPP, 2018a). The antennas utilising 200 MHz bandwidth at 26 GHz can approximately serve 0.15 cars with an advance service package and 0.3 cars with a basic service package. This assumption is supported by spectral efficiency calculations of ultra-dense networks in an urban environment (Yunas, Valkama & Niemelä, 2015) and on the assumption that on average one-third of the total available connected vehicles are active at the same time in peak hours (~ 1000 vehicles/km²)⁵. (Daganzo & Geroliminis, 2008).

The city level hosting requires 4 server cores per sector for baseband processing. Edge computing requires 2 and 3 cores for cars with a basic and advanced service package, respectively. For this, high-performance servers specifically designed for edge computing and equipped with 16 cores are assumed (e.g. the HPE Edgeline EL4000 System).

A simple cost model that includes capital and operational expenditures (CAPEX and OPEX) per square kilometre is included, assuming a Manhattan urban layout with blocks of 200 meters, implying that each square kilometre includes a grid of 5x5 blocks and 25 intersections. The deployment starts with two intersection poles per intersection. Over time, street poles are added between intersections (i.e., along the street) as more capacity is required. Smart poles are connected to baseband processing and edge computing via fibre, to allow for lower-layer splits between user and control plane. Figure 7 shows the deployment layout, including intersection poles and fibre. Based on this layout, a fibre deployment cost of 900 k€/ km² is estimated since each square kilometre requires 5 km of digging and ducting, which on average costs 180 €/m. Table 4 provides estimates for individual cost items which are derived from the literature (Ajibulu et al., 2017; Landertshamer et al., 2019).

Table 4: Cost parameters

	Intersection pole	Street pole	Edge cabinet	Edge server
Components	Base product Data broadband Advanced video surveillance	Base product Data broadband	16 servers	16 cores
CAPEX (€)	21,100	16,100	1000 if cabinet centralized at city level	4,000
OPEX	15% CAPEX	15% CAPEX		

⁵ The model assumes a large city of 600 km², 4 million inhabitants, 450 registered consumer vehicles per 1000 or 1,800,000 vehicles, being one third of them active in peak hours or 1000 vehicles/km²

3.2.6 Revenues

The model assumes a generic revenue sharing scheme like the one existing in Internet platforms, consisting in a monthly subscription fee for accessing the platform with some free services and an additional charge for premium services. For safety and positioning services, this model assumes a basic subscription fee of 15€ which include access to basic safety and general-purpose information. The subscription mode includes a bundling option under which the consumer makes a contract with the platform provider for a predefined amount of time in exchange for a discount in the fee. The following formula describes the amount of discount given the willingness to pay of the consumer for a certain period (Schlereth & El Kihal, 2013):

$$Eq.5 \quad WTP(T) = \begin{cases} aT - \frac{b}{2}T^2, & T \leq \frac{a}{b} \\ \frac{a^2}{2b}, & T > \frac{a}{b} \end{cases}, \text{ where } a \text{ and } b \text{ are parameters giving the shape to the curve, } T \text{ is}$$

the period of time (in years). A graphical representation of this formula is shown in Figure 9.

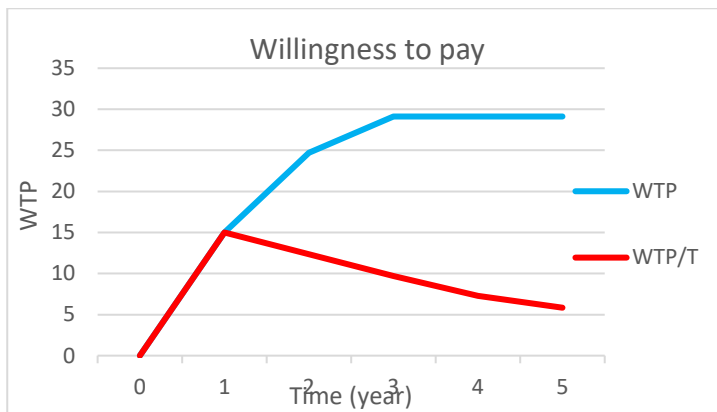


Figure 8: Total monthly willingness to pay (WTP) for subscribing to a service for T periods (in years), with $a=10$ and $b=3$. WTP/T depicts the discounted price given a subscription length. The WTP curve shows that the consumer gives no additional value to a time subscription higher than 3 years.

Besides the subscription fee, service providers ask a monthly fee for their service. If the vehicle has a basic subscription, it has access to basic service providers. If the vehicle has an advanced subscription, it has access to both service providers. The model assumes a maximum number of services a consumer is willing to pay, and the actual number of contracted services will depend on the adoption fraction of service providers (i.e., the more adopted service providers, the higher the diversity of services and the number of contracted services). In the case of a vehicle with advanced subscription, the consumer may contract both advanced and basic services, if the adoption of advanced service providers is considerably lower as compared with basic service providers.

The adoption of data-based service providers produces additional value for consumers. Data-based service providers utilize the data from the platform generated by other services specific to connected vehicles to provide consumers with a more developed version of an existing service. One such example are insurance companies, which may provide intelligent insurances. In fact, safety and positioning services are expected to decrease the amount of accidents for connected vehicles up to 65% (Ricardo & Energy Environment, 2018; Olia, Abdelgawad, Abdulhai & Razavi, 2016). This additional benefit coming from accident decrease may be monetized by both consumers and insurance companies. If the average annual costs for car insurance can range from 800 to 1600 € (Statista, 2018a, 2018b), a 65% reduction can lead to additional benefits for involved stakeholders of 520 -1064 € annually or 43-86€ monthly per vehicle. The

model assumes that half of these benefits is appropriated by the platform owner (21-43€ month/vehicle). The consumer gets part of these benefits by a decreased insurance payment in he /she is subscribed to the required services.

Figure 9 graphically describes the existing cash flows between participant stakeholders of the analysed smart city platform.

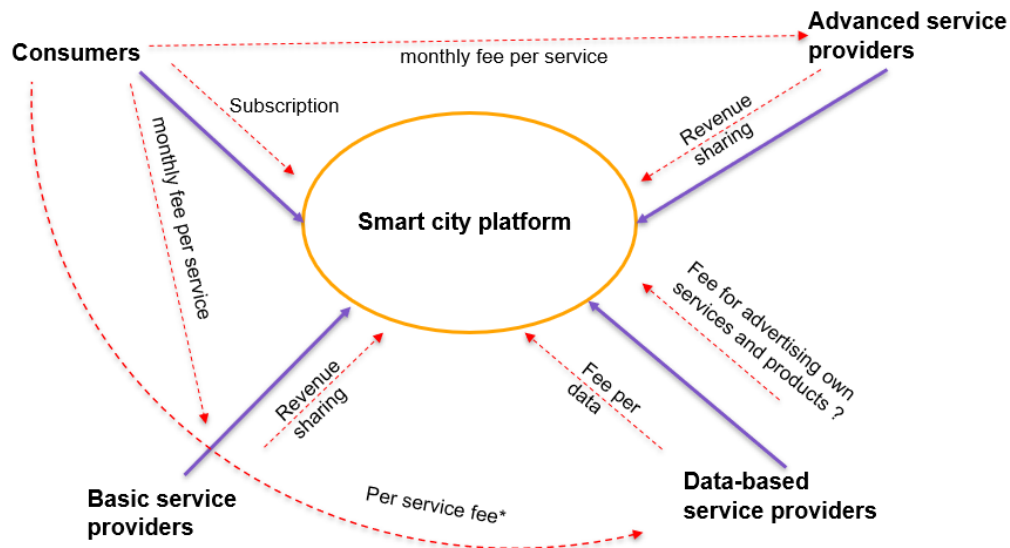


Figure 9: Cash flows logic between parties in the platform

4. Analysis and Results

4.1 Scenarios

This section performs a sensitivity analysis of the most critical parameters affecting the adoption of a smart city platform by both consumer vehicles and service providers.

- Subscription length: describes the average amount of time after which a consumer re-evaluates the decision on staying in the platform or leaving.
- Data sharing: describes how easy is to reuse the data obtained from one type of service to develop another type of service. In concrete, it is defined as a ratio describing the amount of data which is transferable from basic to advanced vehicles and service providers and from advanced to basic vehicles and service providers. In general, it is easier to utilise the data from a more advanced type of service to a more basic version than the opposite case.
- Data caducity: describes the amount of time (in years) after which the data coming to the platform become obsolete.
- Capacity over-dimensioning describes the existing buffer in network capacity to respond to a quick increase in demand. In the model, the capacity (i.e. number of antennas and the corresponding amount of network elements) is built when an increase in the number of subscriptions is observed, and it takes a lapse of time (3 months) for its completion.

Table 5: Main parameters of base scenario

Parameter	Value in the base scenario
Subscription length (years)	2
Data sharing (%)	From basic to advanced: 30%, From advanced to basic: 50%
Data caducity (years)	2
Capacity over dimensioning (%)	10%

4.2 Scenario results

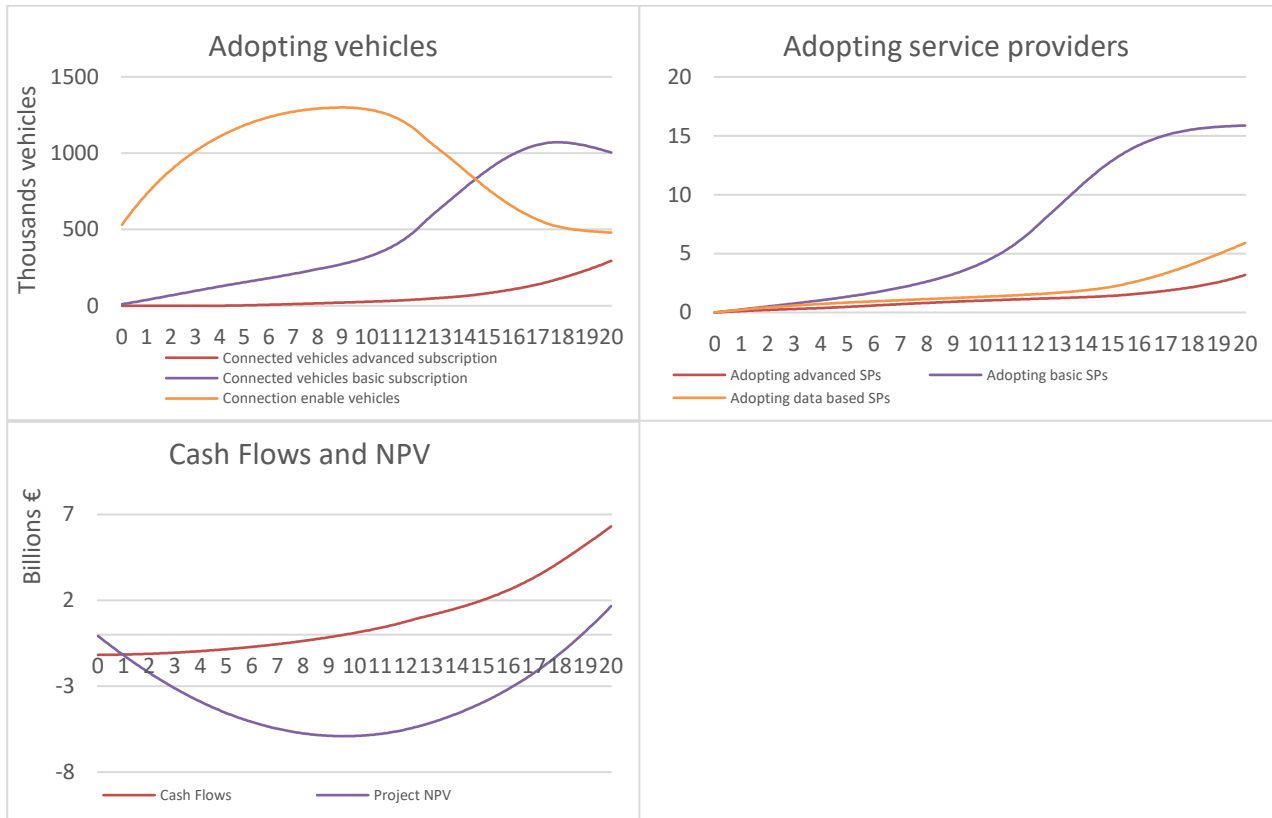


Figure 10: Results for base scenario

This section presents the results for the analysed scenarios. Figure 10 shows the adoption curves for vehicles and service providers with its corresponding cash flows and Net Present Value for the base scenario. This Figure shows that the adoption of a smart city platform for connected vehicles is a slow-moving process and capital demanding. In its base scenario, basic connected cars adopt such platform after 10 years and advanced vehicles after 20 years. The same is true for basic and advanced service providers. Data-based service providers join the platform lightly faster than advanced service providers because they need can already develop their services with basic data, but they require advanced data for developing their service offer further. In terms of net present value, the project turns into positive after 18 years, reaching 1.6 billion € after 20 years.

Figure 11-Figure 14 present the performed sensitivity analysis for selected parameters of interest. Figure 11 performs a sensitivity analysis on subscription length, considering the corresponding tariff discount described by Eq.5 and shows that an increase in subscription length has a major impact on vehicle adoption as compared with the baseline scenario. By incorporating a voluntary bundling option into the service subscription contract in exchange for a discount, the platform manager may speed up the adoption of advanced vehicles and service providers incentivising larger revenues in the long term.

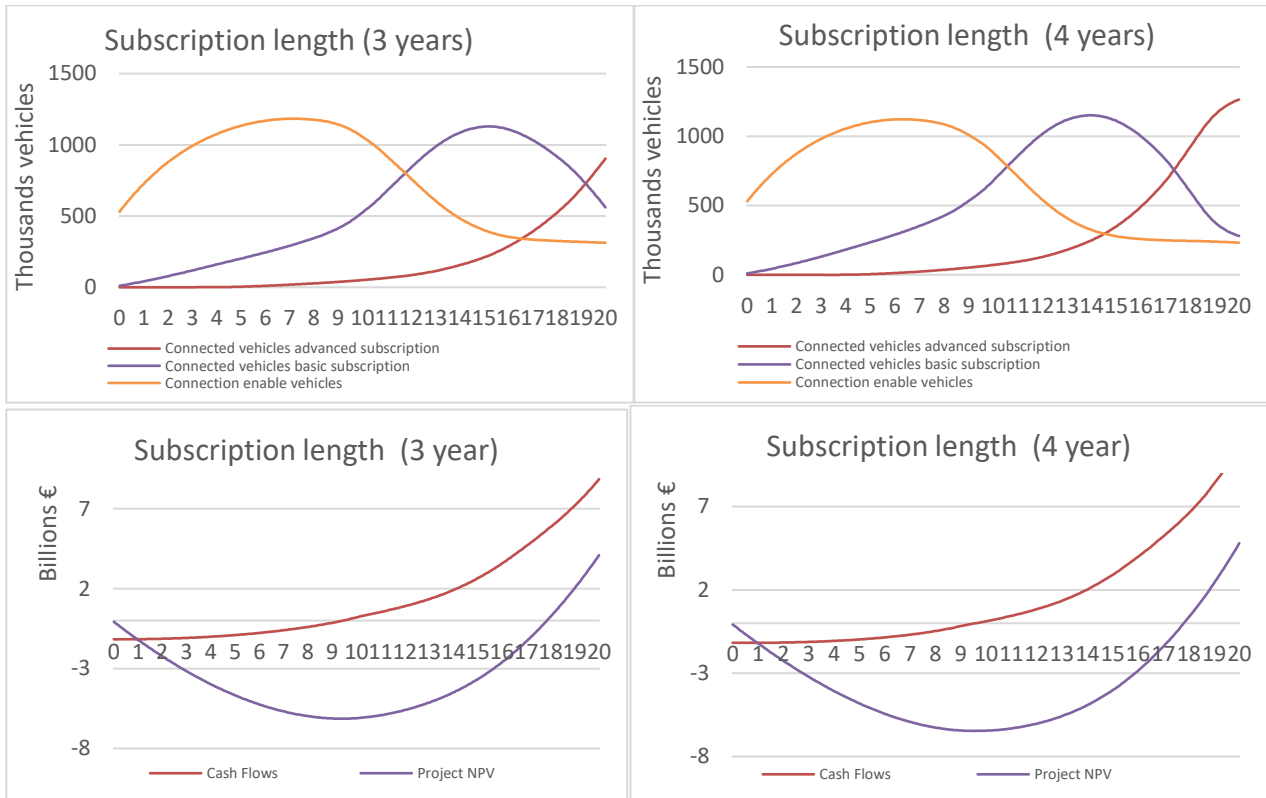


Figure 11: Results for subscription length scenario

Figure 12 performs a sensitivity analysis on data sharing by varying the amount of data which can be reused between different types of vehicles and service providers. From basic to advanced, the analysis varies from 30% to 60% and 0%. From advanced to basic, the analysis varies from 50% to 100% and 0%. The Figure shows as a result that re-utilisation of data enabled by the platform speed up the adoption of advanced vehicles and service providers in the long term. On the contrary, by avoiding data re-utilisation between different types of services drastically slows down the adoption process of advanced vehicles and services. A similar observation can be made by Figure 13, where a poor utilisation of the data depicted in the model by data caducity time may stop the adoption of advanced vehicles and services. On the contrary, the adoption of such vehicles and services is facilitated by permitting an efficient utilisation of the data (i.e. caducity time of 4 years).

On the infrastructure side, Figure 14 evidence a minor impact of capacity over dimensioning on the adoption speed, however, at higher costs of infrastructure investments and having an overall negative impact on future cash flows and NPV. Finally, Figure 15 describes the results for an optimistic scenario, which includes a combination of long subscription length, long data caducity time and high data sharing ratio resulting in an expected quicker adoption process; however, still taking a considerable amount of time (9 years for positive cash flows and 16 years for a positive NPV).



Figure 12: Results for data sharing scenario

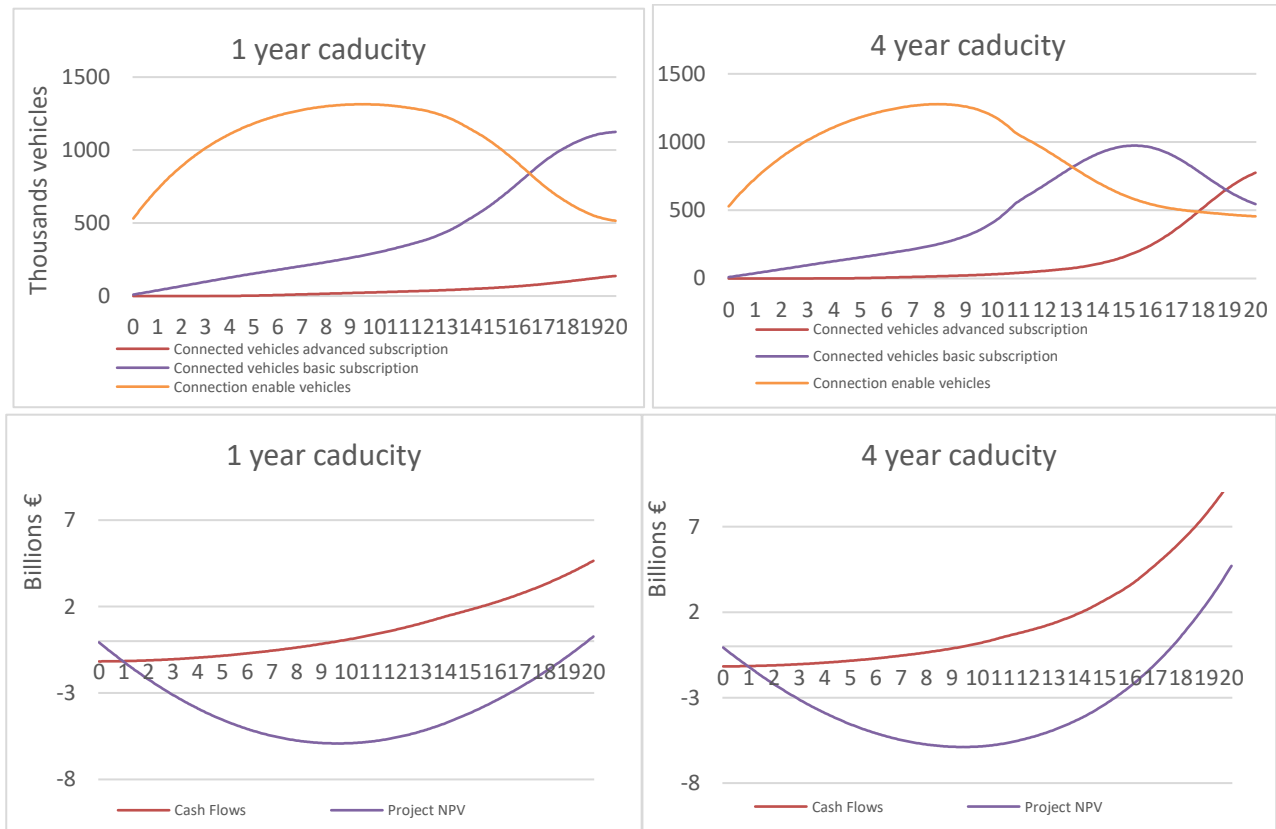


Figure 13: Results for data caducity scenario

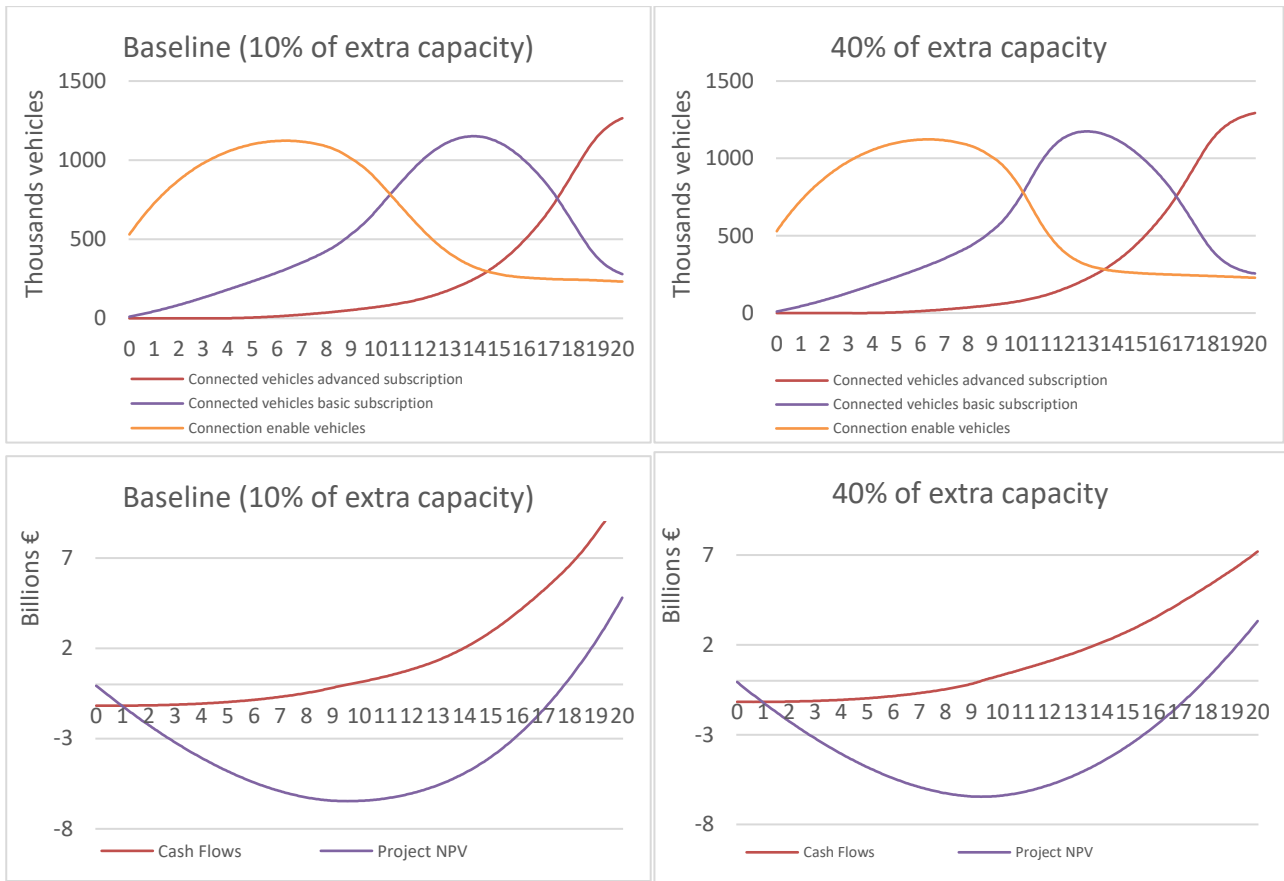


Figure 14: Results for capacity over dimensioning scenario

Table 6: parameters of optimistic scenario

Parameter	Value in base scenario
Subscription length (years)	4
Data sharing (%)	From basic to advanced: 60%, From advanced to basic: 100%
Data caducity (years)	4
Capacity over dimensioning (%)	10%

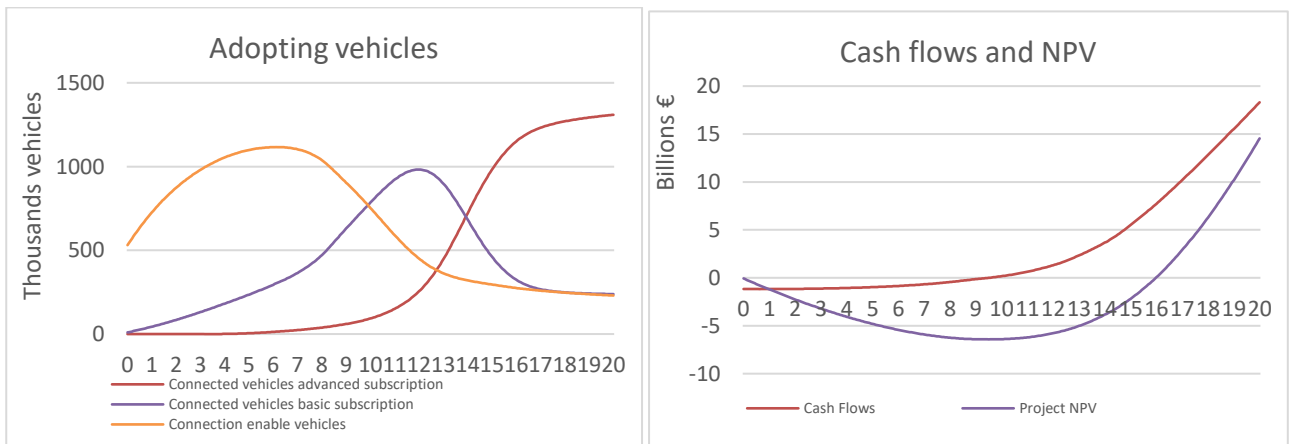


Figure 15: Results for the optimistic scenario

5. Discussion and conclusions

The adoption of a smart city platform for C-V2X services demands high investment and involves high uncertainties. This study analyses the dynamics of its adoption to assess the requirements for a successful deployment, including both technical and economic issues. The performed analysis highlights three factors that may speed up the process of adoption. On the commercial side, customer loyalty practices such as bundling may have a long-term impact on adoption speed. Thus, it may anticipate the generation of positive cash flow by stimulating different sides of the platform to create value. On the platform side, data sharing and its efficient utilisation incentivise user adoption and value creation. The analysed case accentuates the importance of data sharing even between different types of services, representing a major challenge for all involved stakeholders to achieve a higher degree of cooperation and coordination. Finally, in the infrastructure side, this analysis points out the existence of an optimal level of investment that fulfils the technical requirements while avoiding an excess of investment due to over-dimensioning.

Overall, a smart city platform adoption for C-V2X services is a long-term process, even in its more optimistic scenarios; however, it possesses high potential for creating new social benefits in the long term. The adoption of the analysed platform may be thought as an evolutionary process involving the development of basic and more advanced business models that gradually increase value creation, such as sensor as a service, analytics as a service, product as a service, etc.

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7. Appendixes

7.1 Model

