Bringing the Efficiency of Electricity Market Mechanisms
to
Multimodal Mobility across
Congested Transportation Systems

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Abstract

A central challenge facing Mobility as a Service (MaaS) is mispricing of its a core input: the use of scarce road space. A transparent real-time market for road use is essential for MaaS to reach its full potential. We focus on how network-wide, real-time markets for road use support MaaS, and how such markets can be developed.

In our proposed network-management scheme, roadway tolls (for entire trips – from origin to destination) are determined in a two-stage market hosted by an independent system operator or "ISO". Service providers purchase the product (the right to use a series of road segments at a reasonably specific time of day) in the day-ahead market. In real-time, the market becomes physical and operates under the principle of open access: road capacity cannot be withheld in real time and its use is determined by users' decisions, guided by prices and suggested routings. Real-time road-use prices are computed using clearing prices that balance real-time supply and demand. Those with pre-paid slots can be paid to delay their travel, to create space for high bidders during periods of suddenly low capacity or unexpectedly high demand. Such policies and programs can avoid excessive congestion, provide reliable travel times, and keep traffic moving, especially as automation makes car and truck travel easier.

Such policies are critical in helping cities and regions avoid gridlock. They ensure that travelers internalize congestion externalities, while enabling MaaS and other transport providers to deliver higher-quality mobility service for all travelers. Thoughtful marriage of week-ahead, day-ahead and real-time road pricing for travelers in congested networks can deliver efficient transportation systems that save time and energy, while providing signals for optimal infrastructure investment.

Keywords: Mobility as a service, market design, congestion pricing

1 Introduction

The greatest catalyst for the development of the on-demand economy has been technological innovation in the fields of transportation, delivery, and logistics. U.S. consumers spent $6.8 billion in on-demand transport in 2016, and $14.2 billion in 2017 (Statistica 2018). The global on-demand transport market is expected to reach $290.3 billion by 2025 (Grand View Research 2018). In 2017, investments in on-demand mobility were three times larger than the investments made in the previous 4 years combined (Business Insider 2017).

On-demand goods delivery is also important. In the United States alone, same-day direct-delivery sales to final consumers are projected to reach $4.03 billion in 2018, up from just $0.1 billion in 2014, and will increase substantially over the next 4 years (McKinsey & Company 2018). Goods and passengers compete for scarce road space, and congestion remains an important negative externality that transportation economists have been trying to address for decades.

Mobility as a Service (MaaS), the focus of this article, is a sophisticated model of on-demand transport. The term "MaaS" stands for the platform in which travelers can plan and book door-to-door trip services through a single application called journey planner using a single payment system (Sochor 2015; Hensher 2017; Goodall, et al. 2017). The primary goal of MaaS is to provide demand-responsive mobility services that could improve multi-modal transportation performance (Goodall, et al. 2017; Wang et al., 2018). Currently, many cities around the world are learning about MaaS through pilot projects, e.g., Tuup in Finland; My Cicero in Italy; Moovel in Germany; Whim in Finland; and UbiGo in Sweden (Jittrapirom, et al. 2017). A few have advanced into the commercial stage. The widespread adoption of MaaS promises to reduce the social cost of transport by improving both public- and privately-provided mobility—greatly enhancing societal well-being.

There are uncertainties surrounding MaaS that planners must confront to realize the full benefits of this transformation in transport. A central challenge is to address current mispricing of the core input to MaaS: the use of scarce road space. There is currently no systematic, transparent market for allocating the use of road space. The outcome is severe congestion in urban centers imposing massive costs on society. These costs could be substantially reduced with a real-time locational pricing system based on efficient pricing: the price at each time and location is the marginal value of service at the point where supply and demand balance.

In a developed MaaS market, service providers – companies offering a service to consumers –construct the optimal trip chains for each service request. This includes scheduling, routing, and pricing a range of point-to-point, real-time delivery solutions for each prospective traveler. Each solution consists of several individual, yet related, multimodal routes. Those routes may be congested by other travelers using the same or different mode of transport. However, because road space is currently not efficiently priced in real time, neither service providers nor end users receive price signals on the social cost of a trip, including the congestion externality they impose on others (Lindsey and Verhoef, 2000).

Current approaches of charging for road use do not capture the costs of traffic externalities and other impacts of driving (Rouhani and Niemeier, 2014b). That hampers traffic throughput, and thus reduces transport capacity through inefficient scheduling, routing and pricing of MaaS, as well as other modes of transport.

In the absence of a real-time market for road use, stakeholders face significant social costs, including congestion costs (de Palma et al., 2005). Those include (*i*) the network operator, the entity that manages the operation of the network of concern, observes the state of the network, models demand, and adjusts real

time prices to maximize social welfare. The operator may spend billions of dollars in expanding supply to enhance a congested, inefficient system that would not address the underlying problem of "free" road use; (*ii*) MaaS providers would make ill-informed decisions about travel policy and fleet management; and (*iii*) end users would pay for inferior road services indirectly through uncertain delay and increased pollution.

Such inefficiencies will worsen as demand expands with the benefits of MaaS. To tackle this challenge, we analyze a transformative, real-time, road-use pricing scheme. This road-use market will incorporate both spot and forward markets for road use based on the experience with other time-and-location markets that operate under the principle of open access, such as wholesale electricity markets. Capacity markets have been implemented in transportation, specifically in the rail industry to manage rail capacity (Morrison, 2016). However, our proposed approach is fundamentally different from prior suggested solutions.

Using MaaS and new technologies, many opportunities exist to embed efficient dynamic pricing schemes using bundled prices: bundling the individual price of each element in a chained trip and provide end users with a single combined price in real time. Moreover, our proposed approach extends and builds upon a well-established concept in road pricing: dynamic road pricing offers the most effective approach to manage traffic congestion (de Palma et al., 2005; Dong et al., 2011; Rouhani and Niemeier, 2014a).

The paper begins with a brief overview of road pricing, summarizing the existing pricing schemes in both conventional transport and MaaS models. We then review pricing flaws in current transport markets. The third section advances our proposed market design, provides an overview of the market design approach, and proposes an alternative design for the MaaS market. The fourth section investigates barriers to adoption and implementation, and it elaborates on the opportunities policymakers and planners face to further advance the application of market design in MaaS models. We conclude with a summary of implications of the proposed market model.

2 Road pricing

Congestion pricing—the efficient pricing of network capacity—is not a novel concept, and could be traced back to decades ago (Vickrey, 1963). For many decades it has been used in many industries, such as travel and electricity. Each of these markets has its own features.

In urban transport markets, services can be divided into ride-based services and non-ride, facility-based services. Ride-based services, whether provided by publicly-owned transport facilities or by privately-held transport companies, typically are priced in the simplest fashion: a fixed fee for service. A few are priced through "time-of-day" pricing schemes (e.g. Long Island Rail Road's commuter rail system (Brower and Henderson 2004), the Washington Metro, and Uber and Lyft. The ride-sharing services use "surge" and "prime-time" pricing (Chen and Sheldon 2015; Lam and Liu 2018).

In contrast, non-ride, facility-based services often employ dynamic pricing. In the next sections, we provide a summary of congestion pricing practices as well as pricing models of MaaS.

2.1 Road pricing for transport

Road pricing in transport markets is defined as "policies that impose direct charges on road use" (Jones and Hervik 1992). The concept is based on the notion that users should pay the social cost of their use.

The literature categorizes road pricing schemes into: (*i*) area- or zone-based, where vehicles are charged for entering, exiting, or traveling within a certain area, such as the city of London (Hensher and Puckett 2007); (*ii*) cordon-based, where vehicles are tolled to cross a cordon in the inbound, outbound, or both directions,

such as Stockholm's city center (Sabounchi, et al. 2014): (*iii*) distance-based, which charges based on distance travelled, such as trucks operating in Oregon (Rufolo and Kimpel 2008); (*iv*) weight-based, which charges based on carried-weight, such as trucks operating in Kentucky (Conway and Walton 2009); (*v*) road space rationing—rationing peak-period vehicle-trips or vehicle-miles using a revenue-neutral, credit-based system (Han et al., 2010); and (*vi*) facility-based, where tolls are imposed on physical components of transport infrastructure, such as roads, bridges, and tunnels, for example Interstate 15 in San Diego.

The two major goals driving the road-pricing decision are revenue generation and congestion management (Rufolo and Kimpel 2008). Revenue generation seeks funds for long-term investment in transport infrastructure. Congestion management seeks: (*i*) emissions reduction; (*ii*) maximum network throughput via managing peak-hour traffic flows to match supply, encouraging the use of public transit, and incentivizing better trip scheduling over the entire transport system; and (iii) effective land-use management. All share a concern to improve social welfare.

Maximizing social welfare requires efficient pricing: the cost of a trip must equal its marginal social cost (Yang and Huang, 1998). Models typically impose assumptions for tractability, such as: (*i*) the volume-delay function be separable and differentiable; (*ii*) values of time are homogenously distributed across all travelers; and (*iii*) network topology and travel demand are known (Boyles et al. 2010). These simple models are often static, assuming flows are in a steady state or equilibrium in the network. "Determinism of the transport network," a fundamental assumption of static models, ignores the elasticity of demand and price, and hence deprives the model of adaptability to changes in a timely manner.

Users' tendency to maximize their utility by optimizing routes, modes, and time requires consideration of the stochasticity and heterogeneity inherent at all levels of operation (de Palma and Lindsey 2011). Incorporation of stochastic and heterogeneous elements introduces dynamic travel modeling and, therefore, dynamic congestion pricing (Boyles et al. 2010). Dynamic congestion pricing is the determination of time-varying prices to control or otherwise reduce traffic congestion, and hence improve social welfare (Do Chung et al. 2012).

Based on divisions of planning periods, Friesz et al. (2004) classified dynamic road pricing models into within-day (i.e. link flow patterns follow the intra-day process, and the tolls vary by time of day (Wie 2007) and day-to-day time scales (i.e. travelers behavior evolves through a day-to-day adjustment process and may shift network flows from one disequilibrium state to another, or possibly to an equilibrium state (Yang and Zhang 2009).

Full-scale dynamic congestion pricing must consider differentiations concerning trip purposes, travel modes, vehicle types, and trip timing and locations. However, information insufficiency, legal prohibitions, technological challenges, public acceptability have made the pricing variation to reflect all these conditions impractical.

Pricing mechanisms have nevertheless advanced recently. The price of a road can be set as a function of prevailing traffic conditions, which potentially allows the price to adjust to balance supply and demand at each time and location. A complete market-based road pricing system does not exist in practice. The Singapore scheme, as one the most complete real-life examples, is very different from what we propose here. It does not follow a system-wide, real-time road pricing approach. Prices vary by time of day, but are pre-adjusted based on traffic patterns observed historically, not based on real-time supply and demand relationships. The key problem of using historical traffic patterns is that it cannot reflect real-time changes in demand and supply due to weather conditions, traffic incidents, construction sites, etc. that could vary day by day. Moreover, the Singapore scheme acts as a cordon pricing and it does not include all roads, only

expressways and main arterials (Singapore ERP, 2018; Olszewski and Xie, 2005). Moreover, without tracking vehicles at many gantries, the system is far from an efficient and all- inclusive road pricing market.

2.2 Flaws in prevailing pricing mechanisms

Current pricing schemes for both publicly and privately-operated roads are inefficient because they are generally not demand-responsive—users are charged only for peak-hour periods – or the charge remains the same for all periods of day. *Dynamic* road pricing, the temporal flexibility in setting prices, is the key to manage congestion, especially if travel demand is not extremely low or high compared to road capacity. This is ignored in most existing congestion pricing schemes.

Efficient pricing in one market could only mitigate but does not necessarily avoid second-best problems in other transport markets. However, transportation economists generally agree that dynamic congestion pricing schemes, unlike the commonly used existing free-of-charge road management schemes, offer the most efficient approach to manage and operate roads (Do Chung et al. 2012; de Palma et al., 2005; Dong et al., 2011; Rouhani and Niemeier, 2014a). As one prominent example, Van den Berg and Verhoef (2011) show that, under such a scheme, a majority of drivers are better off even without redistributing toll revenues back to them. The study confirms this result even for a second-best pricing scheme, with un-tolled alternatives. It emphasizes the importance of the dynamics of departure-time choices that could be improved effectively with MaaS.

In addition to providing better road services, road pricing schemes could reduce vehicle miles traveled (VMT) through demand management practices and could increase system efficiency by sending efficient price signals to road users. Such improvements also offer a variety of co-benefits such as mitigating travel-related air pollution and GHG emissions and reducing fuel consumption (Rouhani and Niemeier, 2014a).

Examining another important shortcoming in current road management practices, Duncan and Graham (2013) explain why substituting the gas tax with road-use fees would be a more equitable and stable source for funding roads. They argue that better fuel economy, steady tax rates, and the adoption of electric vehicles means that by 2015, the gas tax, the primary source of road financing, will be inadequate to support road infrastructure. Jenn et al. (2015) predict a gas tax reduction of $200 million annually in the US by 2025 because of the adoption of electric vehicles. One solution to this problem is replace the gasoline tax with road-use fees. With the advent of GPS and Internet connectivity in cars, such a scheme is feasible and would lead to more efficient travel behavior, and offer a more stable revenue stream for road construction and maintenance.

Advances in information and communication technologies offer new opportunities to improve travel with inventive market designs. This can be done in conjunction with intelligent transport systems and the vehicle-to-vehicle and vehicle-to-infrastructure schemes (Klein and Ben-Elia 2016).

2.3 Road pricing for MaaS models

Pekuri (2015) identifies several types of MaaS business operations:

i.   Commercial reselling operator: reseller provides the end users with a chain of transport services via an online application (Aapaoja et al. 2017);
ii. Commercial integrating operator: operator acts as a broker and integrates traditional transport services with digital services such as a ticketing and payment platform or real-time routing (Eckhardt et al. 2017). Under this operating model, MaaS is supplied by integrating operators either as their main line of business or as complementary to their service portfolio (CoMaaS 2017 Proceedings).

iii. To enrich the transport service, in this model, the operator integrates its own services by incorporating the transport-related services of others (CoMaaS 2017 Proceedings).

iv. Public private partnership (PPP) operator: the operator integrates various service types provided by telecommunications service providers, mobile service providers, and logistic service providers (CoMaaS 2017 Proceedings). This, as being experienced in Kätevä Seinäjoki/Sito case in Finland, will "enhance and rationalize the services the public actor is taking care of" (CoMaaS 2017 Proceedings) and save public sector costs induced by inefficiency and incomprehensive services.

Through each of the business models, or under any of the operating platforms or revenue streams introduced above, MaaS providers bundle the individual price of each element in a chained trips plan and provide end users with a single price. Bundle pricing, however, is a complex process being managed differently across the existing, and mostly pilot, MaaS platforms.

In Sonera Reissu by Telia Finland, the MaaS provider charges fixed prices for taxis in place and a minor commission fee on re-sold train tickets (Telia Company 2017). Whim by MaaS Global in Finland provides two different monthly mobility packages based on user needs, as well as a pay-per-ride-basis travel option. All the fees and pricing used in the service are based on the bilateral agreements between MaaS Global and transport service providers (MaaS Global 2017). Ylläs Around by Telia Finland also develops all fees and prices based on bilateral agreements it has with transport service providers, such as fixed taxi prices and minor commission fees on re-sold bus trips (Telia Company 2017). UbiGo (Sweden) operates based on bilateral agreements between transport service providers.

Helsinki Regional Transport is somewhat of a MaaS operator since they are organizing and managing multiple public transport modes—trams, subways, local trains, buses and ferries—in the Helsinki area (VTT Finland 2016). Tuup (Finland) has a more advanced pricing mechanism compared to other cases. The provider owns Kyyti taxi-pooling service, hence, has part of a given bundle service dynamically priced, if the bundle includes the Kyyti taxi-pooling service (Honkanen 2017).

Among the existing models, nevertheless, there exists no "full-scale MaaS operator" which requires at least integrating taxis (or equivalent demand-responsive transport services) to ensure greater flexibility.

3 Designing the market

Advancing an optimal pricing mechanism to address all challenges at once would be impractical. This, however, does not justify adoption of the prevailing, yet flawed, pricing mechanisms.

The moment is right for pricing reform for many reasons. Advances in technology allow precise measurement of road use and computation and communication of prices and routes both in real-time and ahead of real time. The millennial generation has shown no fear encountering and successfully adopting radical technologies. Mobile applications have their highest level of penetration. In urban centers, drivers are increasingly using apps such as Google Maps and Waze to plan for their trips (Araújo and Paiva, 2018). Data-sharing and cyber-security concerns are being addressed. Conventional congestion pricing and its corresponding flaws are well-studied and widely recognized. Governments have revealed their interest for innovative road pricing schemes.

The transportation community, therefore, is provided with "an opportunity to build in an appropriate pricing mechanism," as envisioned by Hensher (2018). The early pricing mechanisms of MaaS models should be strategically designed through a step-wise reformation of the prevailing pricing schemes, then modified in time through a learning-by-doing process.

3.1 Market design

A primary motive for market design is to establish rules to achieve objectives and mitigate market failures (Roth 2007). By combining auction and matching theory with behavioral and experimental economics, market design "considers the properties of alternative mechanisms, in terms of efficiency, fairness, incentives, and complexity" (National Bureau of Economic Research).

Market design comes into play when conventional economics, in which the market is viewed as "the confluence of supply and demand," fails to address data-intensive and information-driven transactions. Market design is a response to the ever-increasing complexity of the new era's markets, featuring detailed rules, information transactions, robust game-theoretic knowledge in the design of economic institutions, and computational complexity.

There are many examples in the application of market design. Restructured electricity markets in North America are an excellent example. Indeed, these markets have inspired our modeling approach. The markets have been operating for over a decade, optimally scheduling and dynamically pricing resources in five-minute intervals at every location (Cramton 2017). Despite some fundamental differences between the well-developed market of electricity and the design we propose for transport, electricity market design is a showcase for these methods to price and allocate scarce network resources, facing variation in supply-demand over time and location—properties that are comparable to the transport market.

3.2 Alternative design for the transport market

By harnessing existing technology, MaaS could be priced efficiently. This will complement the successful adoption of any mobility model in the highly competitive market of on-demand transport services.

Ideally, MaaS models price the service package with respect to real time, location, and modal efficiency. An optimal MaaS market should also: provide agents with a transparent and safe ecosystem, maintain adequate thickness (i.e. bring together a large proportion of potential buyers and sellers to produce satisfactory outcomes for both sides of a transaction); and, by giving the market participants adequate time to decide on satisfactory choices, manage the congestion brought by thickness (Roth 2007).

Our proposed transport market builds on Cramton et al. (2017, 2018). We propose a market where one (or several connected) agencies keep track and optimize a road network (much more efficiently than many individuals could) in real time. That is particularly true for a complex network with millions if not billions of different products to "sell" (thousands of origins and destinations multiplied by hundreds of time slots). The centerpiece is the real-time market. The system operator(s) monitors the road network throughout the day and establishes prices for each road segment at each time to balance demand and free-flow supply. Those prices are used to motivate behavior that maximizes the value of the network, which implies efficient road use throughout the day, even recognizing uncertainty coming from lane outages or demand spikes.

As in commodity markets, the real-time market could be supported with forward markets. The forward market is purely financial as the common markets. Forward markets let participants plan and manage risk by taking positions consistent with their underlying demands. Buyers take a financial position. The market resolves itself in real time. For example, you buy your anticipated demand. In real time, a change might occur and you consume at a different time or not at all. Speculation in forward markets is allowed and will not pose a problem if there is sufficient competition (Green and Newbery, 1992; Rouhani and Gao, 2016). However, speculation is not possible in the real-time market as the market is cleared physically and capacity cannot be withheld (for example using a forward purchase). This largely eliminates market power in either market given the competitive market structure, as shown in the electricity market (Wolak, 2000).

The real-time market then provides an efficient and liquid market to settle deviations from forward positions. This is especially important in transport where individual demands often change close to real time, for example a user is ten-minutes late. We anticipate forward markets would be run monthly, weekly, and daily. The forward markets are purely financial. Participants take and adjust positions as information becomes available. Deviations from a participant's forward position are settled at the real time price. Thus, a participant with excellent information about her real-time demand can avoid real-time price risk, by taking a forward position consistent with her real-time demand.

Consumers participate directly and automatically in the real-time through their driving behavior or their selection of mobility services. Participation would be nearly the same as what consumers do now: they drive when and where they want subject to what they know about delays. In the new market, participants would do the same thing, but face prices rather than uncertain delay.

Consumers could also participate directly in the forward markets. However, it makes sense for participants to be given the *option* of selecting a retail plan from competing service providers. The service providers can participate in forward markets to satisfy the demands of their retail customers. MaaS companies would participate in the forward markets and the real-time market to best acquire the road capacity they need to meet consumer demand. Large transport users such as delivery companies would participate in all the markets to maximize their objectives.

In the remainder of this section, we fill in some details.

3.2.1   Key-stakeholders

We classify stakeholders and identify their roles in the proposed business ecosystem.

i. **Governmental authorities**: In most cases, roads are owned by the public sector. Therefore, governments could still play an important role in our proposed market, similar to their roles in electricity markets. Those include monitoring market power, supervising the network operator, and setting high-level strategies about how the market should be evolved, among others.

ii. **Transport network operator**: Defined as the entity makes daily decisions on operational aspects of the transport network.

iii. **Independent system operator** (ISO): The market is conducted by an ISO steering the market for road use with no ownership interest in the road network and no interest in the congestion revenues collected (Cramton et al. 2018).

iv. **Telecommunications service providers**, aka mobile service providers: Information and communication technology providers.

v. **Service providers**:
   a. **Transport network companies**, aka mobility service providers: Companies that have been issued a permit to utilize a digital network to pair end users, via websites and mobile apps, with drivers who provide such services.
   b. **Logistics service providers**: Logistics operators, freight operators, and 3rd party logistic entities.
   c. **MaaS providers**: Entities who bundle trips based on offering the ability to choose the most cost-effective travel decisions. A MaaS provider could also be a transport network company.

vi. **End users**: daily commuters relying on service providers.

Stakeholders could go beyond those listed above. For instance, as a co-benefit, our proposed scheme could act as a congestion management scheme which moderates travel demand and could avoid serious (cost-ineffective) congestion impacts, including traffic queues, noise and air pollution, or even pricing emissions (Rouhani and Niemeier, 2014b). Additionally, our plan includes market instruments to better reflect each

vehicle's external air and noise pollution costs (Ochelen et al., 1998), and to help travelers select more energy-efficient vehicles (e.g., hybrid rather than diesel-fueled pickup trucks), modes, destinations, travel times, and routes. These potential benefits may extend the stakeholders to society as a whole (Rouhani et al., 2016).

3.2.2   Day-ahead market

The day-ahead market is primarily for service providers voluntarily submitting bids and offering to buy transport services (i.e. a slot on a congested road segment at a specific time) a day prior to the time they plan to consume the service. The wholesale market is financially binding, making the bids credible, since successful bids involve a financial commitment from market participants with an option to lock in transport charges at binding day-ahead prices.

The flexibility of day-ahead market rules provides all participants with equal access to the day-ahead market through consistent price signals, and by providing all participants with the ability to submit virtual demand bids and virtual supply offers. In day-ahead markets, hourly clearing prices (i.e. the equilibrium price between supply/demand) are calculated for each hour of the next operating day.

Forward trading mitigates risks. To do this, Service providers will likely develop user apps that enable users to easily and effectively express demand. The Service providers also guide users, both in scheduling future demand as well as routing during real time. Schedules, however, are subject to change in response to unexpected events and new information.

3.2.3   Real-time market

The real-time market is a physical market based on actual road use. This market, in theory, determines the dispatch of resources and dynamically prices road slots throughout the operating day. The real-time market operates based on security-constrained economic resource dispatch and is cleared based on actual system operating conditions over short intervals.

3.2.4   Market mechanism and clearance

Under the proposed design, the road-use price is determined in a two-stage market hosted by an ISO. The prices generated by the ISO are critical in interacting with and guiding consumers making optimized transport choices. To do so, there is an application informing consumers of those prices. The ISO maximizes the value of increasingly scarce road capacity via a dynamic pricing scheme.

The ISO conducts the market: it forms the aggregate demand and matches it with supply to find the clearing price (P*) and quantity (Q*) where supply and demand equilibrate. It adjusts the price to clear the market at each time and location. Based on expectations for real-time activities, the Service providers bid on a product (a slot on a congested road segment at a specific time) in a day-ahead market. Each product is traded in a single-price auction where the Service providers compete and bid on the product they are apt to use.

In real-time, the market becomes physical and operates under the principle of open access—road capacity cannot be withheld in real time and use is determined by the decisions of users, guided by prices and a suggested route. Real-time prices are computed clearing prices that balance real-time supply and demand. The real-time market is used to price and settle deviations from day-ahead plans. The Service providers establish user plans and settle payment. To summarize, the market identifies clearing prices that balance supply and demand for each product at each time.

Figure 1 illustrates the time-sequenced, stepwise actions of agents throughout the proposed markets:
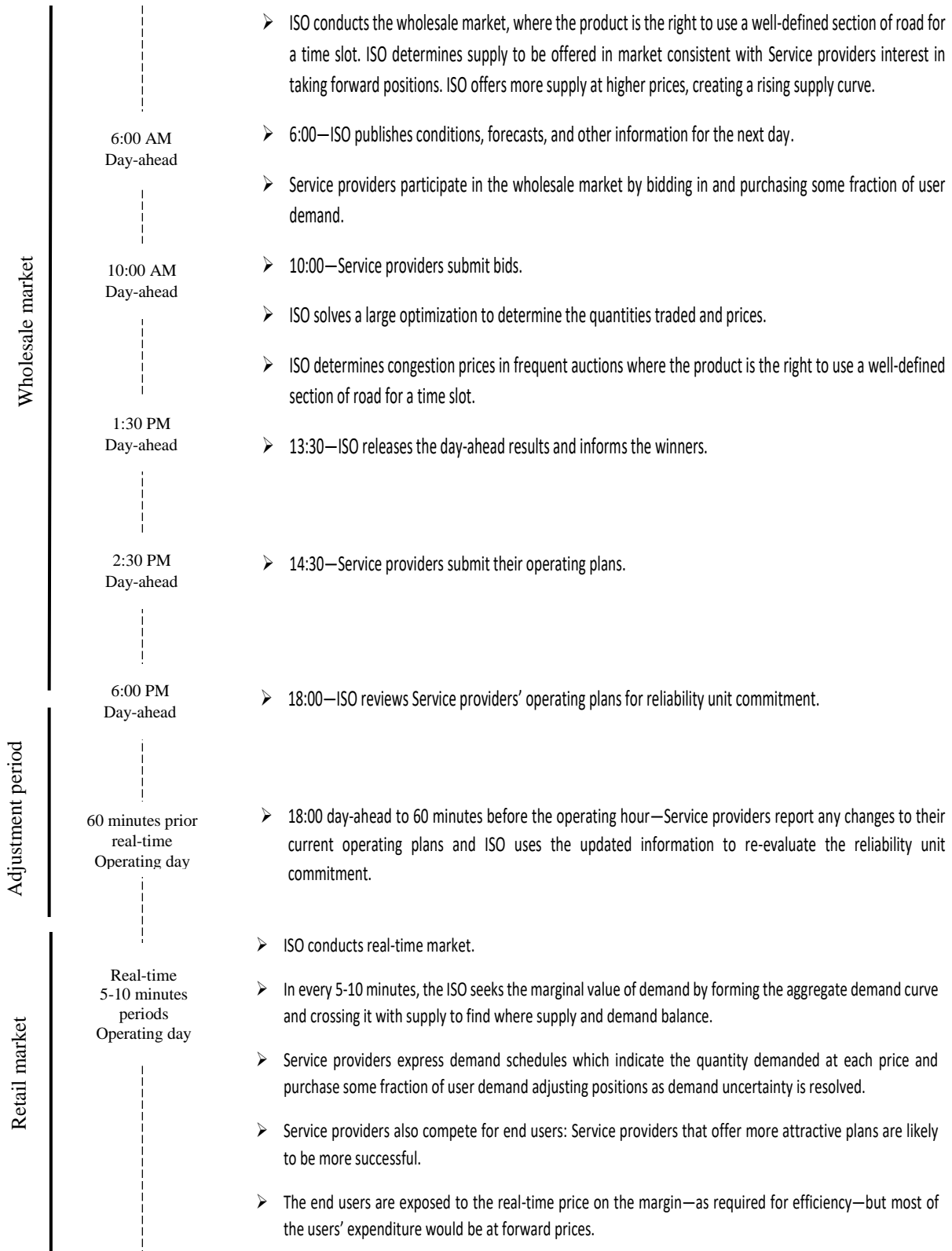
Wholesale market		

Wholesale market

- 6:00 AM Day-ahead

  ➢ ISO conducts the wholesale market, where the product is the right to use a well-defined section of road for a time slot. ISO determines supply to be offered in market consistent with Service providers interest in taking forward positions. ISO offers more supply at higher prices, creating a rising supply curve.

  ➢ 6:00—ISO publishes conditions, forecasts, and other information for the next day.

  ➢ Service providers participate in the wholesale market by bidding in and purchasing some fraction of user demand.

- 10:00 AM Day-ahead

  ➢ 10:00—Service providers submit bids.

  ➢ ISO solves a large optimization to determine the quantities traded and prices.

  ➢ ISO determines congestion prices in frequent auctions where the product is the right to use a well-defined section of road for a time slot.

- 1:30 PM Day-ahead

  ➢ 13:30—ISO releases the day-ahead results and informs the winners.

- 2:30 PM Day-ahead

  ➢ 14:30—Service providers submit their operating plans.

- 6:00 PM Day-ahead

  ➢ 18:00—ISO reviews Service providers' operating plans for reliability unit commitment.

Adjustment period

- 60 minutes prior real-time Operating day

  ➢ 18:00 day-ahead to 60 minutes before the operating hour—Service providers report any changes to their current operating plans and ISO uses the updated information to re-evaluate the reliability unit commitment.

Retail market

- Real-time 5-10 minutes periods Operating day

  ➢ ISO conducts real-time market.

  ➢ In every 5-10 minutes, the ISO seeks the marginal value of demand by forming the aggregate demand curve and crossing it with supply to find where supply and demand balance.

  ➢ Service providers express demand schedules which indicate the quantity demanded at each price and purchase some fraction of user demand adjusting positions as demand uncertainty is resolved.

  ➢ Service providers also compete for end users: Service providers that offer more attractive plans are likely to be more successful.

  ➢ The end users are exposed to the real-time price on the margin—as required for efficiency—but most of the users' expenditure would be at forward prices.

Figure 1. Market mechanism

Under the proposed design, transport is scheduled to maximize the value of the network, and then suggests routings in real time to maximize social value based on real-time conditions. The road-use market thus maximizes the value of our existing transport infrastructure while simultaneously providing valuable price information for network operators and MaaS providers. This motivates efficient long-term transport infrastructure investments.

3.3   Market Objectives

By removing the barrier to free trade, a range of Service providers competes for end users. This creates a 'free market' in which the nominal price of a service is lowered into a new equilibrium price (Heyne et al. 2010) could benefiting the consumer the most (Gabaix and Laibson 2006). This "market correction" is the main deliverable of the market design.

In the short-term, "right pricing" is expected from the market correction process. With the right prices to guide behavior, traffic congestion can be optimized, which leads to higher environmental quality and societal wellbeing and welfare. Right pricing transport also divorces charges for the use of road space from the fuel type used, adopts the basic horizontal-fairness principle (that motorists using roads should pay for them), and allows scarce road space to be allocated to motorists who value it most highly at a time of day; all resulting in higher societal welfare. Right, dynamic pricing is also essential to support newly-introduced transport models, such as MaaS, whose penetration levels depend on price simplicity, transparency, and fairness, the "opportunities" that arise in near real-time markets for road use (Cramton et al. 2018).

In addition to the demand-side benefit of helping to manage traffic flow, variable pricing creates another, supply-side, benefit: it provides information on how much motorists value the use of facilities, and thus reveals the most valuable use of the marginal investment dollar. Therefore, in the long-term, the proposed design will provide essential information to identify which investment options are required, while generating the funds necessary for that investment. This could possibly direct scarce investment resources toward projects where those dollars are most highly valued by road users and away from lower-valued and less-impactful investment decisions. Our proposal thus also addresses one of the most challenging problems facing transportation policy today: the perceived misdirection of scarce public dollars caused by the politicization of spending.

By providing an observable, objective indication of where system expansion should or should not take place, the proposed mechanism also helps depoliticize transport investment, making it more efficient. A consensus has emerged that tolling (and, importantly, public-private partnerships) can provide critical information on where investment should take place, and thus reduce political influences in transport spending (Geddes, 2011).

4   Upcoming challenges and opportunities

4.1   Early adoption challenges of new market design

There are several concerns in early adoption of the proposed market design. Design mistakes, as experienced in California's 2001 electricity crisis (Borenstein et al. 2002), may cost commuters extra costs, hence, lower MaaS's modal share.

Another key-issue corresponds to incentivization of MaaS by publicly-supplied funds. Given the sustainability aspects of using MaaS, relaxation of, or exemptions from, congestion charges (e.g. parking fees or direct tolling) have been "argued" by some MaaS providers (Hensher, 2017). While incentivized service can facilitate MaaS's early adoption, deceptive pricing may mislead the process of right pricing,

and ultimately jeopardize the real opportunity to reform the economics of road user charges and the implementation of congestion pricing.

Upstream firms possessing market power, those market participants forming coalitions, as well as stakeholders that play both as a MaaS provider and TNC, may advance monopoly/oligopoly power and cause quality reductions that raise the costs of 'rivals' (e.g. non-integrated downstream Service providers), and eventually sabotage the market. To address this, the market should be armed with controlling regulations, regulatory constraints on the price, and means of mitigating potential market failure.

4.2   Double-edged sword of competition

A multiplicity of stakeholders interacting in participatory processes increases market competition, yet, scales up the complexity of design and the model's computational cost. The ensuing competition within Mass providers and other Service providers also promotes innovation (Cramton et al. 2017). Innovation helps service providers to better understand user demands, translate user demands into bids in the wholesale market, and develop forward trading strategies to mitigate risk.

Despite this, yet, innovative design creates new technical challenges. Algorithmic trading strategies may threaten market stability. Electronic interaction among strangers in anonymous market environments may also hamper trust and cooperation. As well, cyber security should be well-considered.

Moreover, one might argue that our proposed scheme is prone to the risk of monopolization. Suppose, for example, that bidding were controlled by a small number of companies with market power (e.g., a large online retailer) to use the road space exclusively. First, almost all sustainable transport policies encourage reduced private driving in urban areas because of their externalities (Bainster, 2008; Rouhani, 2009). In fact, our proposed scheme may lead to similar long-run travel behavior changes. Second, the market becomes physical and capacity cannot be withheld in real time. Thus, the online retailer would require enough physical trucks to use 100% of real time capacity in order to prevent the use of others. Moreover, it would be extremely expensive to buy 100% of the forward market. The market structure of roads is highly disaggregated; even the largest users have rather modest market shares. Nonetheless, the market should be monitored by a market operator who would be alert to market power indicators and suggesting solutions if such issues arise.

4.3   Compatibility with other transport markets, modes, and models

Before communities shift to efficient congestion pricing, important issues must be addressed to overcome public and private opposition. Equity and monopolistic pricing tendencies are serious concerns. Both could be addressed by a more advanced schemes like credit-based congestion pricing (Kockelman and Kalmanje, 2005; Gulipalli & Kockelman 2008), where the net revenue raised is redistributed back to travelers, as a travel credit. For example, each adult may receive $40 per month in his/her Toll Tag account, while children above the age of 8 could receive $20 each month.

These accounts can be easily merged by household members to support road use by household vehicles as well as other travel demands, like bus and train passes, short-term car rentals, and shared-bike system use, enabling a variety of modes and within-region consumption. Credits may sunset at the end of each month (to avoid long-term banking, if that is deemed and issue), and residents of the region are on a rolling cycle (so credits are released uniformly in time, across different residents, to avoid demand peaking at the end of each month and to make use of unused credits suddenly). Credits cannot be cashed out, to avoid fraudulent use (by travelers who have not been residing in the region that month), but may be acknowledged by certain local businesses (like movie theatres), to enable more sustainable travel choices. Excess credits may also be donated to special causes (like single-parent working households with long commutes).

In addition to the coordination with other modes of transport, our proposed market can be extended to all modes of transport. In fact, in order to offer a more efficient transportation system, policy makers should pursue a more inclusive approach. In practice, however, the inclusion of other modes could pose social and political concerns because public transportation by nature should serve all without imposing high charges. Moreover, the operation and coordination of all transport modes together will become very complex.

Our proposed system could also be aligned with future automated systems. Autonomous Vehicles (AVs) offer the following new opportunities for MaaS and for our proposed scheme: (*i*) Full AVs (level 4-5) could provide a convenient and inexpensive door-to-door transportation services for users since the price of AV-based mobility service could be lowered because there is no need for drivers; (*ii*) with a full range of a vehicle to vehicle (V2V) connectivity and the improved forecasting power of MaaS, transportation systems could move from user equilibrium to system optimum. The connectivity allows all AVs to simultaneously share road conditions and choose their alternative paths efficiently; and (*iii*) from a data collection perspective, road-traffic data have never been as available as the public-transportation data, which is collected by card usages. Because of the higher-quality data available by AV systems, the system operator-ISO in our proposed scheme could predict and plan for road conditions more accurately. Despite the discussed opportunities, the prediction regarding AVs' impacts on the MaaS platform is challenging because of uncertainties in the future technology and policy. Specifically, any demand projection for AVs regarding their impacts on vehicle-miles-traveled (VMT) is still controversial because of two opposing potential impacts of AVs: (*i*) the induced travel demand versus; (*ii*) the increased efficiency. The impact varies depending on the country's policy, the strategy of service providers, the local predominant driving behavior, the AV penetration rate, and public acceptance (Simoni et al., 2019; Gurumurthy et al., 2019).

4.4   Policy options and multi-layer governing system

Separate from the ISO, successful network-wide pricing approach requires appropriate institutional and organizational structures. Price information alone is insufficient to ensure efficient investment choices. We view the set of institutional structure undergirding network-wide pricing as its system of governance.

Our proposal presents unique challenges. Network-wide congestion pricing requires integrating other modes of transport, including transit, into transportation decisions. This will require the adoption of mixed public-private governance structures. Moreover, if prices do not sufficiently incentivize the Maas sharing concept, then users may be encouraged to use personal motorized vehicles within the MaaS system for trips that were previously done with public transport or non-motorized modes, mainly for comfort and reduced travel-time.

The above also suggests that MaaS is likely to influence the most efficient allocation of investment decisions between the electric and transportation infrastructure. Under MaaS, there should be more coordination across investments in those two types of infrastructure. A careful analysis of policy options also requires understanding of relevant behavioral forces. This is critical in predicting how policy change impacts outcomes. Delayed trips might cause problems in terms of coordination costs in rare cases but would not substantially increase complexity. Real-time use would be recorded and the standard settlement would be made by selling the forward position at the earlier time (at the real time price) and buying the delayed travel at the real-time price. Prices are apt to be highly stable in nearby time slots, therefore, the automatic adjustment is typically small and could be on a monthly basis. Nevertheless, substantial differences in prices could occur, just as in our current transport systems, it is possible that leaving at a different moment could increase travel time substantially.

4.5 Behavioral economic engineering of MaaS market design

There is enormous laboratory and field evidence that individuals respond to market incentives in ways that lead to efficient outcomes—if the market is appropriately designed. The available behavioral evidence regarding markets for road use generally comes to the same conclusion, although more work should be done to address traffic-specific challenges and opportunities.

Almost all highly-controlled laboratory traffic experiments focus on simple, repeated coordination games, sometimes without any pricing (Selten et al. 2007; Chmura and Pitz 2004; Schneider and Weimann 2004; Rapoport et al. 2004), or with very simple price schemes (Gabuthy et al. 2006; Hartman 2009). The experiments typically induce identical driver preferences, inelastic demand and deterministic supply (but see Lopez 2017). This line of work generally confirms that people respond to incentives in line with qualitative predictions from game-theoretic models.

Most laboratory experiments, so far, did not study behavior along different relevant dimensions in transport markets, such as time and space. Nevertheless, field experiments are increasingly filling the gap. They often use GPS data to measure the behavioral effects of various congestion pricing schemes. For instance, Martin and Thorne (2017) installed GPS responders in 1,400 vehicles in Melbourne and measured how drivers responded to being charged for road use. The authors found that constant charges do not much affect peak-time behavior, but charges targeted at peak times do reduce congestion (see also Kreindler 2017). These studies can strengthen trust in congestion pricing as compared to laboratory experiments, survey studies (Small et al. 2005) and self-reported travel diaries (Karlström and Franklin 2009). Yet we caution that they may come with their own limitations. For instance, the overall traffic situation is hardly affected by the experiment treatments because only relatively few motorists participate in these experiments. This makes it very difficult to measure actual behavioral trade-offs between time, risk and price, as would be experienced with an optimal congestion pricing scheme. Also, long-term adjustments to congestion pricing, which tend to reduce individual and social costs, are not accounted for in any of those experimental studies.

Road pricing has also been studied without imposing experimental control. For instance, Foreman (2016) found a substitution from peak to off-peak times on the San Francisco Oakland Bridge after the introduction of time-varying tolls. Cordon charges have been found to be effective in reducing congestion in London (Leape 2006) and Milan (Gibson and Carnovale 2005). Yet here, too, the data are of only limited value when the goal is to learn about the impact of optimal transport market design. One reason is that prices in those systems typically do not respond optimally to supply and demand conditions. So, it would be extremely valuable to study human behavior in a test-bed laboratory or in settings that implement efficient markets.

Individual motivational and cognitive biases in judgment and behavior in traffic contexts need to be better understood. Otherwise, it might turn out to be difficult to gain sufficient political and driver acceptance. For instance, motorists seem to sometimes severely underestimate the benefits of transport markets. This often leads to an overwhelmingly negative public attitude towards initiatives that promote market-based road pricing, but an overwhelmingly positive attitude once motorists have had a chance to experience actual market processes and outcomes (Eliasson 2014). This is in line with recent laboratory studies showing that voters often demand bad policy—and reject policies that would help them to overcome social dilemmas and thereby increase welfare—because they tend to underappreciate equilibrium effects (Dal Bò et al. 2018). It is important to understand how such cognitive biases emerge and how they can be addressed to avoid being stuck with the status-quo. Similarly, it is also important to address privacy and equity concerns, such as human drivers' reluctance to accept pricing mechanisms that may seem unfair, and to deal with issues such as cognitive constraints to information processing that require specifically designed user apps and feedback mechanisms to elicit more reliable demand information.

There are still important gaps in our knowledge about how humans respond to transport markets. Nevertheless, overall, the existing experimental and empirical literature confirms the general strong effectiveness and efficiency of market-based pricing mechanisms to address traffic and other externalities.

4.6 Interdependency between transport and electricity markets

Our prediction is that the future of ground transport will include an electrified system with a large penetration of autonomous, on-demand, and shared mobility. Electricity will be generated predominantly from such renewable sources as wind and solar radiation with strong support from batteries and demand response from smart homes. Electrical power generation and distribution are also expected to decentralize into a system of micro- and smart-grids.

The appropriate mechanism design in markets for transport services and electricity, *inter alia*, may help deliver the necessary understanding. It becomes primary to examine how appropriately regulated, decentralized, market-based decision making—that exploits information made available in real-time through digital technologies—can facilitate a transition to resilient, interdependent systems of transport and power generation and distribution based on new (and still emerging) "clean" technologies. Future research should intend to explore the evolution of these interdependent systems from their present state as they evolve over several decades into the future.

We acknowledge that electricity and transport systems differ in three major ways. First, the structure is different in electricity markets: (*i*) a natural monopolist is required to distribute the electricity; (*ii*) more components operated by different entities (i.e. generation, transportation, and distribution) exist; and (*iii*) the end users essentially use some products and generally do not pay time-of-use for electricity. However, transportation systems are generally owned by the public sector, which acts a natural monopolist. Moreover, fewer components could favor our proposed market in transportation over electricity, and paying for time of use is essential for transportation systems in order to manage congestion.

Second, in an electricity market, a catastrophic collapse is possible when supply and demand do not match or when transmission lines fails. As a result, congestion management is vital. For transport systems, however, congestion management is not essential since surface transportation systems generally survive without management in most cases. However, this does not imply that congestion management is not required.

Third, although variations in supply and demand are common in both electricity and transport systems, there is less variation in transport systems. This implies that market prices will be more stable and congestion management will be more effective in addressing the predictable disequilibrium of demand and supply at peak periods. If there is no variation in supply and demand, then a forward market is not necessary. In reality, however, variations (albeit smaller), exist because of both travel demand and supply variations as a result of changes in travel time scheduling, traffic incidents, construction work, weather conditions, and operational disruptions.

5 Conclusion

The primary objective of this paper is to examine how a regulated market for road use can facilitate the transition to a sustainable model of transport (Banister, 2008), one based on new, and still emerging, on-demand mobility. The market harnesses the power of real-time measurement of use together with advances in communication and computation to allow efficient pricing. The transport transformation will lead to welfare improvements from increased traffic flows, reduced congestion, reduced energy use and emissions, and greater equity in the availability of public services.

We apply market design methods to road pricing. The market is highly complementary with MaaS opportunities. Road use is priced at each time and location to balance supply and demand. This approach allows for much better use of the road network, an essential input to MaaS.

As in modern commodity markets, the market real-time market is supported with forward markets that allow participants to plan and manage risk. Participants take financial positions in these forward markets (monthly, weekly, and daily) and then the real-time market is used determine efficient use and settle deviations from the forward plans. With millions of participants, the real-time response to prices is smooth and the system operator is able to establish prices to balance supply and demand. Importantly, consumer behavior is not restricted in any way. Consumers can drive whenever and wherever they want and enjoy free-flow throughput. Participants can ignore prices if they wish, but most take prices into account, just as they take their delay costs into account when commuting.

The proposed market design allows the direct expression of drivers' underlying economics and constraints, then joint optimization of all preferences to maximize social welfare. Our proposed pricing mechanism thus also mitigates one of the most challenging problems facing transport policy today: the political spending of public funds because of the absent information about the economic value of network elements.

A complete system of scheduling, routing, and congestion pricing may seem like a radical idea. Such market design, however, has been successfully implemented in electricity markets for over a decade. This will be the inevitable future of road pricing.

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