A novel peer-to-peer congestion pricing marketplace enabled by vehicle-automation

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Abstract

This paper proposes a novel concept of congestion pricing based on voluntary peer-to-peer exchange of money between motorists in exchange for one ceding priority to another in a traffic stream. While in the classical congestion charging paradigm payments are compulsory and flow only towards the system operator, in the proposed marketplace participation is voluntary and motorists directly compensate each other. A particular motorist may find that he/she is a 'payer' at certain points in a given journey and a 'payee' at others.

Humans would not be expected to successfully seek, negotiate and execute a continuous series of peer-to-peer trades involving micro-payments while also handling the cognitively-demanding task of driving; real-world implementation will therefore require vehicles operating under fully-automated control in both the longitudinal and lateral dimensions during the time periods that they seek and engage in trades. The automated vehicle control algorithms must be sufficiently intelligent and adaptable to enable alternative maneuvers on short timescales, given the inherent uncertainty of whether or not a potential trade will in fact be executed. The peer-to-peer trading would be executed algorithmically, subject to strategic-level guidance given by a vehicle's occupant(s) regarding the occupant's relative valuation of money and priority in the traffic stream.

In this paper we detail the prospective marketplace and present a simple simulation model to expose its properties. We show that the proposed peer-to-peer marketplace could lead to both desirable and undesirable outcomes; which of these would be predominant is a matter requiring empirical study. The paper concludes with a discussion of further research needs to refine and develop these concepts into practice.

Key words

Peer-to-peer, Congestion pricing, Automated vehicle

1. Introduction

The notion of charging motorists to occupy space on congested road networks has been a longstanding part of mainstream transportation research (Pigou 1920, Walters 1961, Vickrey 1963, Johnson 1964). Congestion charging on a road network is typically designed to be implemented by the responsible public-sector entity. Except for special cases where parallel 'charged' and 'free' lanes exist, in which the charge is set dynamically in response to real-time network conditions, congestion pricing as typically implemented on road network is a relatively blunt instrument for managing demand, for a variety of reasons. In many cases the price charged does not vary in real-time with demand, despite the fact that congestion does. The London (United Kingdom) congestion charge, for instance, is a fixed price during the time that charging is in operation, regardless of network conditions. Price discrimination between different travelers is also relatively uncommon in practice; variation in individual people's willingness-to-pay for priority through particular network paths at particular times is therefore not accommodated.

In this paper, we propose a novel form of congestion pricing based on a peer-to-peer marketplace that enables voluntary trading between adjacent vehicles of their relative position in a traffic stream in exchange for micro-payments. Such a system builds on earlier research into network governance strategies under high levels of vehicle automation. To the authors' knowledge, prior literature has not addressed peer-to-peer traffic-control mechanisms that can operate in the absence of intermediation via the road network manager.

The properties of the proposed peer-to-peer marketplace are exposed via a simple simulation analysis. The prospective system has both desirable and undesirable properties; undesirable properties arise due to the benefits of each trade accruing to the vehicles that are willing participants in the trade whereas some of the costs it imposes accrue to vehicles which are downstream of (i.e. behind) the vehicles participating in the trade and who do not choose whether or not to bear such costs. This paper presents a necessarily stylized and straightforward analysis of the issues raised by the prospective marketplace; a broader program of research will be required to better understand its likely operations and consequences.

The prospective marketplace requires that vehicles engaged in seeking and executing trades must be operating under automated control (i.e. not under real-time control by a human 'driver') in both the longitudinal and lateral dimensions. In the taxonomy developed by the US' National Highway Traffic Safety Administration (NHTSA 2013), this is classified as 'Level 2' automation[2]. The system does not require vehicles that operate exclusively under automated control for an entire journey ('Level 4' automation), because a vehicle that transitions from automated-control to human-control would simply stop transmitting (and responding to) offers from leading and following vehicles.

The remainder of this paper is structured as follows: Section 2 presents background on congestion pricing instruments. Section 3 describes the simulation methods used in the

[2] We note that NHTSA uses the example of *"adaptive cruise control in combination with lane centering"* (NHTSA 2013, page 5) to describe 'Level 2' automation. The prospective peer-to-peer marketplace presented in this paper would, however, require lateral control that is different than traditional 'lane centering', because the trading vehicles would each be required to occupy the margins (rather than the center) of a lane.

quantitative analysis, the results of which are presented in Section 4. Section 5 concludes the paper with a brief summary and discussion of future research needs.

2. Background

Congestion pricing on road networks has traditionally been conceived of as a mechanism by which the system operator charges each motorist a fee, which must vary across time in some way to distinguish it from a classical road toll. In exchange for their payment the motorist is granted access to travel where and when the charging is operable Pigou 1920, Walters 1961, Vickrey 1963, Johnson 1964, Teodorovic and Edara 2007, Brownstone and Small 2005, Gomez-Ibanez 1992, Graham et al. 2008). Systems typically involve either charging motorists to travel on a specific linear corridor (e.g. the State Route 91 tolled lanes in Orange County, CA, cf. (Brownstone and Small 2005) or a geographic area encompassed by a defined cordon line (e.g. the scheme in Central London, UK, cf. [TfL 2014]). Price may vary temporally according to a pre-defined schedule, or may vary dynamically in response to real-time network conditions.

When a road network manager introduces classical congestion pricing, not all travellers will be made better off though the aim is that on balance there will be a net increase in welfare. A common strategy is for the entity that collects the revenues to agree to dedicate some or all of the net revenue in ways that compensate groups that are not directly made better-off through the implementation of pricing (King et al. 2007).

Credit-based congestion pricing, a relatively sophisticated form of congestion pricing, merits highlighting in this discussion. As proposed by Kockelman and Kalmanje (2005), such a system would involve a central system administrator allocating each driver with monthly driving credits that they then 'spend' on driving (with the 'costs' of driving being time- and link-specific). If they do not exhaust their allocation of credits, they can either carry them over to future periods or sell them to drivers that wish to purchase additional credits. The credits proposed by Kockelman/Kalmanje are a commodity product (i.e. not spatio-temporally heterogeneous); they are fungible in the sense that they can be 'spent' by driving on any link in the road network (albeit at variable rates).

Congestion pricing is one way of allocating priority through a traffic network to specific vehicles (those that have paid the charge), though in practice other mechanisms are more widely used to provide differential degrees of network priority. Police and other emergency vehicles use sirens and flashing lights to direct that other motorists cede priority (NB: Systems to draw on vehicle-to-vehicle communications to assist with path-clearing for emergency vehicles have been proposed, cf. [Jordan et al. 2013]). The use of sirens and lights is not in all cases limited to emergency situations; the motorcade of a government minister may, for instance, legally use sirens and lights to direct other motorists to give way. Vehicle design can also facilitate priority; motorcycles' narrow width enables them, in certain circumstances, to maneuver past standing queues of four-wheel traffic (Lee and Polak 2012). Physical design is also used to give network priority to certain vehicle types; bus and bicycle lanes are common examples. Tolled road corridors frequently allow vehicle equipped with an electronic tag to bypass toll plazas at which cash-paying motorists must stop. Another example of network priority is the dedication of specific lanes to only permit-carrying traffic. In Moscow lanes appeared (popularly termed *Zil lanes*) during the latter Soviet period that were restricted for use by only cars carrying high Soviet officials. A contemporary example occurred during the 2012 Olympics in London, where lanes were re-allocated from general vehicular traffic, for the exclusive use of *"officials, international media, VIPs, and emergency vehicles"* (Hirst 2012).

Finally, there is an emerging body of literature on the use of connected vehicle technology to cooperatively route vehicles through either entire networks (Du et al. 2014) or individual intersections. Goodall et al. (2013) propose a method that optimizes traditional phase-based traffic signal control by drawing on vehicle-to-infrastructure communications in which vehicles communicate their position, heading and speed. *Virtual traffic lights* have also been recently proposed, in which either vehicle-to-vehicle (Ferreira and d'Orey 2012, Sinha et al. 2013) or vehicle-to-infrastructure (Li et al. 2013, Dresner and Stone 2004) communications allow vehicles to avoid colliding with one another at an intersection through dynamic coordination rather than allocation of priority by a fixed traffic signal. Centrally-administered auctions of intersection-priority have also been proposed (Bazzan et al. 2012, Vasirani and Ossowski 2012) in which an intersection controller (a fixed piece of infrastructure) auctions priority to approaching vehicles. This control strategy would lead to welfare gains relative to a classical first-come-first-served traffic-management strategy if it successfully aligns priority through an intersection with motorists' willingness-to-pay. Balan and Luke (2006) present an extension to this literature by proposing a mechanism in which vehicles that have been subject to delays at signalized intersections *previously* during a given journey receive priority (as allocated by the central system operator) at signalized intersections they reach *later* in the same journey.

In summary, the present research extends from the existing body of literature by introducing a peer-to-peer concept of congestion pricing that allocates network priority in an economically-efficient manner with no requirement for the road network manager to take any action.

3. Methods

In order to expose the operational properties of a prospective automation-enabled system of peer-to-peer congestion pricing, a straightforward, small-scale simulation model was developed with the specification described in this section. The specific parameter values that govern the simulation were synthetic but plausible; important elements of the research agenda addressing this topic are 1) to develop refined methods that relax the restrictive assumptions, and 2) to develop distributions of parameter values that are empirically grounded (such as through revealed-preference or stated-preference techniques).

The schematic network geometry is a single unidirectional arbitrarily-long road network link of constant cross-section; flow is not interrupted by any traffic control devices. The key design criterion is that the link's cross-section accommodates a single lane of traffic when vehicles are travelling (as would be typical) in the center of the lane, but is wide enough to allow two vehicles abreast if the lead vehicle willingly chooses to maneuver to one side of the lane to allow the following vehicle to pass. Even a typical 12-foot wide lane (the standard for U.S. freeways per the AASHTO Green Book, cf. [AASHTO 2011]) is approximately wide enough to accommodate two 2015 Toyota Camrys (chosen as a representative mid-size sedan) abreast without encroachment onto adjacent lanes or roadside shoulders (the 2015 Camry's width is 71.7 inches [Toyota 2014a], and for comparison the 2015 Toyota Yaris, typical of subcompact cars, is 66.7 inches in width [Toyota 2014b][3]. In practice, however, adding in tolerance for oscillations associated with road surface imperfections and vehicle suspensions would be likely to imply a degree of horizontal encroachment when two mid-size sedans (or wider vehicles) engage in a transaction.

A notional ten-vehicle traffic stream was analyzed in the main analysis, with a larger system (100 vehicles) employed in sensitivity analyses presented in Table 4. All vehicles were randomly assigned a willingness-to-pay (WTP) value in units of cents per advancing one position in the traffic stream; this value remained constant for each vehicle throughout the simulation. In the interests of simplicity, it was assumed that each vehicle's WTP to advance one position in the traffic stream was equal (but of opposite sign) to its willingness-to-accept (WTA) to move back one position in the traffic stream. In a real-world design of the prospective system, automated-car occupants could indicate their WTP values to the trading system through the use of a dial that could be manually adjusted up or down to indicate, for instance, increased WTP because one's arrival at his/her destination has become more time-sensitive than previously realized. Design of appropriate user interfaces for the prospective system is an important avenue for future research; the key criterion is that the human provides strategic-level guidance rather than deciding whether or not to execute specific trades. The trading decisions are made algorithmically; this is similar in some ways to algorithmic trading in financial markets, with the key difference being that trading of positions in traffic streams is spatio-temporally heterogeneous in ways that financial instruments are not.

The WTP values were specified such that a limited amount of trading took place; in the main analysis each of the ten vehicles' WTP was drawn from a uniform distribution with the following bounds: 0.75 cents per position-in-traffic-stream to 2.25 cents position-in-traffic-stream. The envelope between these lower and upper boundary values was chosen for consistency with current guidance regarding Value-of-Time (VoT). Trottenberg (2011) recommends that a value of $23.90/hour of personal travel (equal to 0.66 cents per second) be used in U.S. analyses. In order to determine the value of moving forward one position in the traffic stream, a lower bound for the minimum headway between autonomous vehicles can be calculated to be the length of the vehicle (19 feet, using the standard dimensions for a *Passenger Car* design vehicle in the *AASHTO Green Book*, cf. [AASHTO 2011]) plus the gap between the lead and following vehicles. This gap can be no less (in units of time) than the refresh rate of the autonomous car's sensing technology. If a value of 10Hz is used (per Levinson 2011) and a [congested] travel speed of 5 miles per hour (7 feet per second) is assumed, the longitudinal spacing between a following and a leading autonomous vehicle can be no smaller than 0.7 feet in the interests of collision avoidance, even if engineering tolerances to account for possible differential rates of deceleration are neglected. At 5 mph, 2.8 seconds are required to travel 19.7 feet (19 feet + 0.7 feet). Therefore, the value of moving forward a position in the traffic stream would be equal to 1.85 cents for a vehicle with a value of time of $23.90 (2.8 seconds * 0.66 cents per second = 1.85 cents).[4] Following similar calculations, it can be determined that the implied VoT of

[3] The quoted widths of the two sample vehicles do not take the additional width of side-view mirrors into account.

[4] It can be shown, by calculations analogous to those in this paragraph but for different speeds, that the value of advancing forward a position in the traffic stream is inversely related to travel speed, and that therefore the largest potential gains from a prospective P2P-trading system would occur in low-speed conditions.

vehicles in this system ranged from a low of $11.48/hour for Vehicle #2 to a high of $27.71 for Vehicle #3).

A critical design decision for a prospective system is the protocol for inter-vehicle communication interactions. There is nothing in principle that limits the inter-vehicle communications to bilateral interactions (i.e. when two vehicles communicating exclusively with each other in an attempt to negotiate a mutually-beneficial trade, with neither simultaneously engaging in negotiations with any other vehicles). Computing demands and rate of inter-vehicle communications per unit time increase rapidly, however. The simulation runs for 10 discrete time steps; in the interest of simplicity in each time-step each vehicle attempt to negotiate with either the vehicle they are following or the vehicle that is following them. The pairing of vehicles that attempt trades with each other alternates; in the first time step, the vehicles in position #1 and #2 attempt to trade with each other, the vehicles in position #3 and #4 attempt the same, and so on. Then, in the second time step the vehicles in positions #2 and #3 attempt to trade with each other, as do the vehicles in positions #4 and #5, and so on. Therefore, in even-numbered time steps the vehicles in position #1 and #10 (the front and back of the ten-vehicle traffic stream, respectively) do not seek to trade with other vehicles in the traffic stream and therefore simply remain in their position during the time step. In practice, the value of the quantum of time required to negotiate and then perform trades will vary by a set of idiosyncratic factors, such as communications latency, computing/processing times, and the acceleration/deceleration performance of the individual vehicles.

In order to expose the complexity introduced by individual vehicles engaging in multiple negotiations simultaneously, consider a situation where a vehicle in position #2 is negotiating with the vehicle in position #1 to swap places to advance into position #1, and concurrently negotiating with the vehicle in position #3 to move backwards in the traffic stream to position #3. If (neglecting transactions costs for the moment) $WTP_3 > WTP_2 > WTP_1$, the vehicle in position #2 has two advantageous trades from which to select; moving forward or moving backward are both preferable to remaining in place in position #2. At this point, the vehicle in position #2 must decide which of these actions to do (presumably on the basis of which offers the larger gains from trading) and then communicate its selected course of action to both the vehicles in positions #1 and #3 so that they can act accordingly. Despite these two vehicles (in position #1 and #3) knowing that there are gains that would accrue from trading positions with the vehicle in position #2, they must wait until that vehicle communicates its decision to them before they can begin undertaking the physical maneuver. Following similar logic, complexity further increases if $WTP_4 > WTP_3 > WTP_2 > WTP_1$, and more so if $WTP_5 > WTP_4 > WTP_3 > WTP_2 > WTP_1$, and so on; the dimensionality of this problem of coordinating actions amongst multiple vehicles has no natural upper bound (except that imposed by the number of vehicles in the system that are simultaneously negotiating interdependent trades, which will be limited by whether the distance between vehicles is greater than the range of the communications).

During the simulation, the following events take place during each discrete time step (see also Figure 1):

1) Of each pair of lead/following vehicles that are negotiating with one another, the lead vehicle communicates to the vehicle following it the lead vehicle's WTA to allow the following vehicle to pass. Simultaneously, the following vehicle communicates its WTP to pass the vehicle it is following. If $WTA_{leading\ vehicle} \geq WTP_{following\ vehicle}$, the

vehicles determine that no mutually-beneficial transaction is possible during this time step. (NB: The "≥" operator is used rather than ">" as we define that no trade will take place if both vehicles are indifferent to making the trade).

2) If, however, $WTA_{leading\ vehicle} < WTP_{following\ vehicle}$, each of the two vehicles then determine whether a maneuver to trade places in the traffic stream is physically possible, and if so the transaction costs it would bear to perform the physical maneuver required to swap places. The vehicles then simultaneously communicate their respective transaction costs to each other. If $\left(WTA_{leading\ vehicle} - Transaction\ costs_{leading\ vehicle}\right) \geq \left(WTP_{following\ vehicle} - Transaction\ costs_{following\ vehicle}\right)$, the vehicles determine that no mutually-beneficial transaction is possible during this time step. As in action #1 (the first action in this listing), the "≥" operator is used rather than ">" as we define that no trade will take place if both vehicles are indifferent to making the trade, after taking transaction costs into account.
3) If, however, $\left(WTA_{leading\ vehicle} - Transaction\ costs_{leading\ vehicle}\right) < \left(WTP_{following\ vehicle} - Transaction\ costs_{following\ vehicle}\right)$ then the vehicles agree on a price P such that $\left(WTA_{leading\ vehicle} - Transaction\ costs_{leading\ vehicle}\right) < P < \left(WTP_{following\ vehicle} - Transaction\ costs_{following\ vehicle}\right)$. As described later in this section, for the purposes of this simulation it was assumed that the price at which trades are transacted is in all cases midway between $WTA_{leading\ vehicle}$ and $WTP_{following\ vehicle}$.
4) After agreeing on the price of the trade, the trade is then consummated by the lead vehicle maneuvering in such a way that allows the following vehicle to [safely] pass it (i.e. the vehicles physically swap their positions in the traffic stream. The payment for the trade then takes place via an electronic deposit from the 'payer' vehicle (the vehicle that moves forward one position in the traffic stream as a consequence of the trade) to the 'payee' vehicle (the vehicle that moves backward one position in the traffic stream as a consequence of the trade).

The prospective system would inherently involve non-zero transaction costs, because in consummating a trade either the lead vehicle in a trade would decelerate to allow the following vehicle to travel past it, or the lead vehicle would maintain a constant speed and the following vehicle would accelerate to execute the maneuver, or some combination of both deceleration and acceleration. This maneuvering would necessarily involve excess fuel consumption beyond the level if both vehicles simply traveled at a constant rate of speed, and the costs of this excess fuel consumption (in addition to wear to the vehicles' drivetrains) would comprise part of the transaction costs. It is worth noting that steer-by-wire technology (Mitchell et al. 2010) combined with automotive design in which all four wheels are steerable will allow new types of maneuvers that would increase the efficiency of the prospective trading mechanism by reducing the transaction costs in certain instances. For instance, a vehicle in a stationary queue that wishes to swap its position with the vehicle behind them could do so by rotating all four wheels 90 degrees and maneuvering laterally (without any longitudinal movement required), thus allowing the following vehicle to pass.

In the simulation analysis undertaken for this study, transaction costs of each prospective trade were drawn from a uniform distribution bounded between zero and one cent. Trades were only consummated if the WTP of the following vehicle exceeded the WTA of the lead vehicle by a larger amount than the transaction cost.

The costs of the information-technology (IT) infrastructure required by the prospective peer-to-peer trading system would manifest themselves as a second category of transaction costs. For instance, the market-making apps and websites that facilitate peer-to-peer carsharing (in which drivers that wish to use another person's car pay them for its use) retain a fraction of each monetary exchange through its systems in order to cover the costs of designing, administering and maintaining the systems (hardware, software, support staffing, etc.) required to administer the marketplace (Getaround 2014, RelayRides 2014). But, as the individual trades in the prospective trading between 'payer' and 'payee' vehicles would not necessarily be transacted through a central clearinghouse some other mechanism (aside from retaining a fraction of the value exchanged in each trade) may be needed to support the IT systems; if there is an absence or under-provision of the stream of revenue for system-support, it could mean the system does not operate optimally due to under-investment.

The simulation analysis presented in this paper incorporates an assumption that positions in the traffic stream are traded at the midpoint between the (lower) WTP value of the 'selling' vehicle (the lead vehicle, which as the result of the trade will maneuver backwards in the traffic stream) and the (higher) WTP of the 'buying' vehicle (the following vehicle, which as the result of the trade will maneuver forwards in the traffic stream). This is a simplifying assumption; it is possible in principle for the transacted price to be anywhere in the range between the two WTP values. If the frequency of the vehicle-to-vehicle communications were rapid enough, it would be possible in principle for the two vehicles to negotiate a transacted price that benefits one of the trading vehicles more than the other. We leave further exposition of this particular issue as a topic for future research.

The prospective system would need some mechanism to ensure that both parties to a trade follow through with their agreed action. A mechanism is required that would deter the 'payer' vehicle from advancing in the traffic stream while neglecting to actually make the payment to the 'payee' vehicle, and likewise to prevent the 'payee' vehicle from collecting the agreed payment from the 'payer' vehicle without also maneuvering to allow the 'payer' vehicle to pass. One possibility is for both actions to happen as close to simultaneously as is feasible, so that neither party needs to expose itself to the possibility of the other party misrepresenting its intentions. Another possibility if simultaneity is not practical is for each vehicle (meaning each vehicle's *user account*, which would belong to a specific person) to, after a successful trade, provide a positive rating to the other vehicle. By accruing a large number of positive ratings, a vehicle can credibly assert to prospective trading partners its trustworthiness. If a ratings system were implemented, it could in principle be managed either by a central system operator, or as a peer-to-peer system where a positive rating given by one vehicle to another contains a unique and verifiable code that would allow it to credibly assert trustworthiness to a prospective trading partner without the prospective trading partner needing to verify the asserted positive ratings via a central system operator. Further investigation of this issue is left as a matter for the future research agenda.

4. Results

In this section we present results from both a single representative 'example' run of the ten-vehicle main simulation analysis and from a set of 100 runs, as well as sensitivity analysis (presented in Table 4) using a larger 100-vehicle system. The single 'example run' refers to a single draw from each of the stochastic distributions (WTPs and transaction costs). While the results from this example run are therefore sensitive to the single idiosyncratic draw that was taken from each distribution at the appropriate point in the simulation, the advantage is that it allows exposition, at the disaggregate level (i.e. results are shown in this section for each vehicle) of the full sequence of events that took place in the simulation. The input WTP values of each vehicle in the traffic stream from the example run are shown in Table 1.

Figure 2 shows the trajectory of each vehicle in the main analysis through the traffic stream during the course of the example run (the 10 time steps). Variation in the number of trades in each time step can be clearly seen; no mutually-beneficial trades were identified in time step #1 and therefore no trades took place. At the other extreme, five trades occurred in time step #3 (meaning that all ten vehicles took part in a maneuver).

Figure 2 shows that in the example run vehicle #10 starts in position #10 (in time step #1 vehicle numbering and position numbering are identical) but has a relatively high WTP value and therefore progresses forwards through the traffic stream such that by the end it is in position #4. It is not surprising that, as can be seen in Table 2, this same vehicle paid out a net amount of 10.18 ¢ to the vehicles in the traffic stream with which it executed trades[5]. Though the aggregate monetary values in the simulation (shown in Table 2) are quite small, it must be borne in mind that they arise from a small-scale system in which a small number of vehicles interacted with one another relatively briefly. For comparison purposes, there were 3,067 billion vehicle-miles of travel in the U.S. in 2015 (USDOT 2016). We also note that if a fixed VoT is assumed, then a vehicle's WTP to advance a single position in a traffic stream is higher at lower speeds, and therefore the amounts exchanged via the peer-to-peer marketplace are larger. The final row of Table 2 presents summary results from 100 simulation runs of the ten-vehicle system, in the interest of demonstrating the effects of stochasticity of the simulation inputs.

During the example run, eight of the ten vehicles moved either only forwards or backwards through the traffic stream. Two vehicles, however, (#8 and #9) traded with other vehicles (not each other) to move forward in at least one time step and with others to move backward in other time steps. Though this analysis is based on an assumption of time-invariant WTP values, in principle a vehicle's occupants could at any point in time modify the WTP that their vehicle communicates to prospective trading partners, and therefore flexibly modulate the degree to which they either advance through the traffic stream (paying those vehicles that allow passing) or fall back (receiving payments from those vehicles that wish to pass). The effect of the volatile transaction costs can also be seen – for instance, vehicle #7 follows directly behind vehicle #1 from timestep #5 but they do not swap places until timestep #9.

[5] The values in Table 2 for all but the final row are generated by summing across each of the individual trades shown by vehicles exchanging positions in Figure 1. The values in the final row are generated by the same procedure, and subsequently averaged across 100 runs of the ten-vehicle simulation analysis.

Table 2 shows that each vehicle generated a net surplus from their trading actions in the example run. By definition each trade is voluntary and hence generates a positive amount of value (i.e. surplus) to both parties to the transaction. Therefore, any vehicle engaging in trading activity (all vehicles did so in this simulation run) must generate a positive amount of surplus in aggregate from the trades to which they are a party. The maneuvers required to trade places may, however, generate turbulence in the traffic stream and therefore impose some degree of delay on vehicles that are upstream (i.e. behind in the traffic stream). This delay is *involuntary*; it occurs by definition to all vehicles that are neither the buyer nor the seller of a position in the traffic stream (and whether they are driven by a person or operate in automated mode) but rather they simply find themselves upstream of the two transacting vehicles. In this simulation analysis we did not place an arbitrary monetary value on this externality, however the number of instances that each vehicle is involuntarily subject to delay due to downstream trading activity is shown in the right-most column of Table 2. In the example run, several vehicles are subject to more than 10 specific instances of delay caused by others – this is due to multiple downstream trades taking place during individual time steps. The consequence is that the system as a whole provides a net increase in welfare relative to a no-trading counterfactual if the net surplus from trading aggregated across all vehicles (8.43 ¢ in the example simulation run, as seen in Table 2) exceeds the aggregate cost of delays involuntarily imposed on upstream vehicles.

Furthermore, even if the system as a whole provides net increases in welfare, it is possible that individual vehicles might be worse off than they would be if no trading took place. For instance, a vehicle with a human driver would not take part in any trades, but could find itself upstream of position-trading between automated-operation vehicles and therefore subject to delays imposed by that trading activity. A welfare-increasing solution to account for congestion externalities from trading would require that the buyer and/or seller of each transaction are somehow made to bear the cost of congestion that they impose on other vehicles. This is a non-trivial task, however, because vehicles affected by a downstream trade might, for instance, strategically misrepresent their WTP value in an effort to extract arbitrarily large compensation from the downstream vehicles that executed the trade. Alternatively, requiring that all vehicles affected by a trade voluntarily agree to it before it can take place would be difficult to enforce because upstream vehicles are not physically blocking the downstream vehicles that would be the trade's main parties (the buyer and seller). Additionally, the complexity of the required negotiations would increase rapidly if more than two vehicles are party to a transaction. In summary, policies to ensure efficiency despite the likely effects of causing upstream delays are an important direction for the next phase of research.

The presence of congestion externalities that two trading vehicles may unilaterally impose on upstream vehicles introduces a further important system property. All upstream vehicles, whether human-driven or in automated operation, are subject to additional delays caused by downstream trading between automated vehicles. Therefore, participation in the prospective trading system is incentivized in a self-reinforcing manner: Net benefits can only accrue to the two parties of each consummated trade, while net costs accrue to all downstream vehicles regardless of operating mode (human-driven or automated-operation) and also regardless of whether or not a vehicle makes itself available to possibly take part in trading.

Another possible effect that could lead to welfare losses could occur because what would be traded in the prospective peer-to-peer marketplace are not property rights *per se*, but rather physical occupancy of a moving slot of public road space. Since access to a road-space slot is not owned by any individual motorist, motorists (under present operating standards for public roads) cannot be excluded from attempting to occupy it. It could therefore be that some people would respond to the incentive to generate income through a behaviour analogous to 'squatting', i.e. by instructing their automated vehicle (possibly, in some scenarios of vehicle automation, operating without a human occupant; cf. [Fagnant and Kockelman 2014]) to travel on congested parts of a road network and repeatedly cede priority in the traffic stream in the partial or sole interest of generating income. Whether or not such behaviour would be incentivized is a purely empirical question, which would depend on the relative magnitude of expected vehicle operating costs and expected income from trading. In the limit a person might place their stationary vehicle such that it blocks the moving lane of a roadway, in order to then trade with (i.e. generate revenue from) vehicles that wish to proceed past it. If it is found empirically that there are instances where such behavior occurs and can be shown to lead to welfare losses, this would present a justification for some form of regulation of the peer-to-peer trading system, or other regulations that specify acceptable on-road behavior more prescriptively than today's rules of the road. An example of the latter would be more widespread use and enforcement of minimum speed limits. This issue is complex and not addressed in this simulation analysis; it is an important item for the research agenda.

Whereas Table 2 contains results at the level of individual vehicles, Table 3 presents system-level metrics from the 100 simulation runs. We report both mean values (the rightmost column) as well as a range of percentile points of the distribution (5^{th}, 25^{th} 50^{th} [median], 75^{th}, and 95^{th}). The topmost row shows the sorting process whereby higher-WTP vehicles tend to migrate towards the front of the traffic stream (and vice versa for lower-WTP vehicles). By the end of the ten time steps, the mean value of the correlation coefficient between WTP and position-in-traffic-stream is -0.55 (i.e. high-WTP vehicles tend to be near to position #1 and low-WTP vehicles tend to be near position #10). We also see, as would be expected, a strong correlation (a mean value of -0.73) between WTP and net exchange of value (i.e. high-WTP vehicles tend to be net 'payers' whereas low-WTP vehicles tend to be net recipients of payments).

Table 3 also shows a degree of correlation (a mean value of -0.27) between WTP and the number of times that a vehicle is involuntarily subject to delays imposed on it by trades that take place downstream of it. High-WTP vehicles tend to migrate towards the front of the traffic stream; there are relatively few vehicles downstream of them and hence there are relatively few opportunities for downstream trading to involuntarily impose delays (and vice versa for low-WTP vehicles)

Finally, Table 4 shows the results of a sensitivity analysis in which the number of vehicles is increased to 100 and the distributions of both WTP and transaction costs are systematically varied. Several noteworthy relationships can be seen. First, as the distribution of WTP widens (simulated via increases in the upper boundary of the uniform distribution), both the gross amount exchanged and the aggregate surplus from trading increase more than proportionally, with the aggregate surplus increasing more sharply. Second, as the WTP distribution widens the system outputs become less volatile (i.e. the ratio of the mean output metrics shown in Table 4 to their respective standard deviations statistics tend to decrease). Third, as the same distribution gets wider, the average amount of surplus-per-trade increases (i.e. each trade generates, on average, a larger amount of value). Fourth, increases in transaction costs intuitively result in decreased levels of trading activity (numbers of trades) and value (surplus) generated, with this effect being stronger when the distribution of WTP is relatively narrow and diminishing as the distribution of WTP widens.

5. Discussion and Conclusions

This paper presents a novel concept that draws on the unique computing and vehicle-control capabilities enabled by a prospective set of connected and automated road vehicles to facilitate a peer-to-peer congestion pricing mechanism. Unlike traditional congestion pricing mechanisms and strategies for allocating network priority, this marketplace does not require that the entity with responsibility for overseeing the road network functions as a central system operator that sets pricing policies and administers its operation. An entity would need to design and maintain the system's physical and software components, but it would not have to be a public sector body and it need not set operational policies (the key requirement is that it enable a structured communications channel between participating vehicles). Participation in the system as well as all trading of micro-payments both take place on a voluntary peer-to-peer basis between vehicles rather than, as in traditional 'tolling' mechanisms used in congestion pricing, payments flowing solely from [drivers of] individual vehicles towards the central system operator.

The simulation analysis employed in this paper's exposition of the marketplace's system-level properties is simple and straightforward, and therefore subject to a number of limitations discussed here. Further research is needed to establish the prospective system's properties under less-restrictive but more computationally burdensome assumptions governing the system's operations, and also empirically-realistic operating parameters. For instance, temporal volatility in willingness-to-pay was not modelled; doing so could result in a more realistic simulation if there were empirical support on which to base the amount of volatility that is introduced. The same is also true with regards to differences between the instructions motorists' give to their vehicle's trading agent regarding their willingness-to-pay and willingness-to-accept values. The simulation analysis presented here is limited in its treatment of the communications protocol, and it will be necessary to design the details of communications protocol of the prospective system, and to then test it in a more complex simulation environment that explicitly accounted for vehicle kinematics. This is a non-trivial research direction, however, as at present a consensus has not yet emerged regarding the values of the kinematic parameters that will govern the motion of automated vehicles, and it is also likely that there will be much variability between different manufacturers' operational parameters. If simulation analysis along these lines suggests that the prospective marketplace can be operable in a suitably-large set of geometric and traffic-demand conditions and also provides suitably-large benefits to its participants and/or net benefits at the system-level (including all road users, whether or not they take part in the marketplace), a test bed application in a controlled environment would be a logical next step in system development.

In the proposed marketplace, travelers who have relatively-high willingness-to-pay for speed in the traffic network tend to migrate forward in the traffic stream (i.e. get to their destinations quicker than otherwise), whereas the opposite occurs for travelers with relatively low willingness-to-pay values. Since willingness-to-pay for travel time savings is thought to correlate positively with one's income level (Mackie et al. 2001), there is potentially an equity issue in that travelers that are better-off financially disproportionately gain a new capability to navigate through congested road networks at higher speed than otherwise. This is true, however, for any congestion pricing instrument that does not have price discrimination against higher-income travelers.

There are potentially other implications for public policy. A jurisdiction that wishes to preclude peer-to-peer trading can simply define it to be an illegal activity. Such a position was recently taken by San Francisco's City Attorney (OSFCA 2014), who served a cease-and-desist demand on a mobile app that connected motorists occupying on-street parking spaces with other motorists willing to pay the parking space's occupant to vacate it and allow them to enter it in their place. The cease-and-desist demand argued that existing law prohibits *"the buying and selling of public street parking spaces"* (OSFCA 2014, p.3); the operator subsequently terminated services in advance of the deadline imposed by the City Attorney (NBC Bay Area 2014). Alternatively, a road network manager that wishes to preclude trading of position in a traffic stream might instead simply design the network in such a way that the physical maneuvers required to swap positions are not possible. For instance, a one-way road that carries a single lane might be re-designed with a reduced width bounded by vertical curbing of suitable height to physically ensure that a following vehicle cannot pass a leading vehicle.

The simulation presented here analyzed a single stream of traffic on a single lane – i.e. all vehicles moving in the same direction. An important issue for future research is to establish the properties of such a system with automated vehicles operating on more complex network features, such as multiple lanes and bottlenecks where traffic streams queue (e.g. stop control at intersections), merge or cross one another (cf. Wang et al. [2015]), and with heterogeneous traffic streams. For instance, consider a scenario with two automated vehicles each approaching the same intersection (which has no control) at the same time, and hence at risk of imminent collision if they both continue on their present trajectories. The outcome if the vehicles are able to negotiate with each other is that the vehicle with higher WTP proceeds through the intersection first, and compensates the vehicle with lower WTP in exchange. This would bear some similarities to the intersection-priority auctions proposed by Balan and Luke (2006), Bazzan et al. (2012), and Vasirani and Ossowski (2012), as all involve structured efforts to align willingness-to-pay with intersection-priority. In general, however, arranging trades between conflicting traffic streams at intersections differs from the single-traffic-stream context studied in this paper in two important respects. First, the negotiations are time-sensitive if the vehicles are in conflicting directions of travel and on trajectories that will lead to imminent collision without evasive action; failed inter-vehicle negotiations would mean that at least one of the vehicles must still adjust their trajectory but without receiving compensation (cf. Sinha et al. 2013 for a detailed discussion of a non-compensated protocol for 'virtual' traffic control). Second, congested intersections are characterized by large numbers of conflicting vehicles. Bilateral negotiations between pairs of vehicles are infeasible; instead each vehicle may have to simultaneously avoid colliding with dozens of other conflicting vehicles to traverse an intersection. Large numbers of vehicles attempting to reach mutually-beneficial trades with each other would require many iterations of inter-vehicle communication to identify and agree on a compatible set of safe and economically-efficient physical maneuvers.

Finally, though the simulation analysis presented in this paper analyzed only car travel, the principles are transferrable to circumstances where traffic streams are heterogeneous (e.g. cars, transit buses, commercial goods vehicles, etc.) Today the most widely-implemented mechanism to provide priority to certain types of road users is to provide the privileged vehicles with a dedicated physical right-of-way (e.g. a bus lane). A more-complex version of the prospective peer-to-peer marketplace could involve a transit bus operating in mixed traffic and negotiating trades with adjacent private cars on behalf of all of the bus's passengers. The bus would identify the aggregate willingness-to-pay of its passengers, negotiate with adjacent cars for priority in the traffic stream on that basis, and then electronically collect and/or distribute any payments to its passengers based on the willingness-to-pay that each passenger has indicated. In principle such a system would be a more-flexible allocation of road space than lanes that are physically-dedicated to pre-specified vehicle types but that take no account of variation between each road user's idiosyncratic willingness-to-pay.

In closing, the authors wish to make clear that we take no view regarding whether the prospective marketplace is a *good* or *bad* idea; the aim of this paper is to expose its properties and to stimulate further research so that entrepreneurs and policymakers have better knowledge of its consequences.

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Tables and Figures

	Willingness-to-pay (defined to be identical to willingness-to-accept) for moving one slot forward (or backward) in traffic stream
Vehicle #1	1.18 ¢ (cents)
Vehicle #2	0.90 ¢
Vehicle #3	2.16 ¢
Vehicle #4	1.19 ¢
Vehicle #5	1.88 ¢
Vehicle #6	1.24 ¢
Vehicle #7	2.07 ¢
Vehicle #8	1.72 ¢
Vehicle #9	1.64 ¢
Vehicle #10	2.08 ¢

Table 1: Listing of individual vehicle's willingness-to-pay (WTP) values (cents per position in traffic stream) as employed in the example run of the simulation analysis (traffic stream of 10 vehicles)

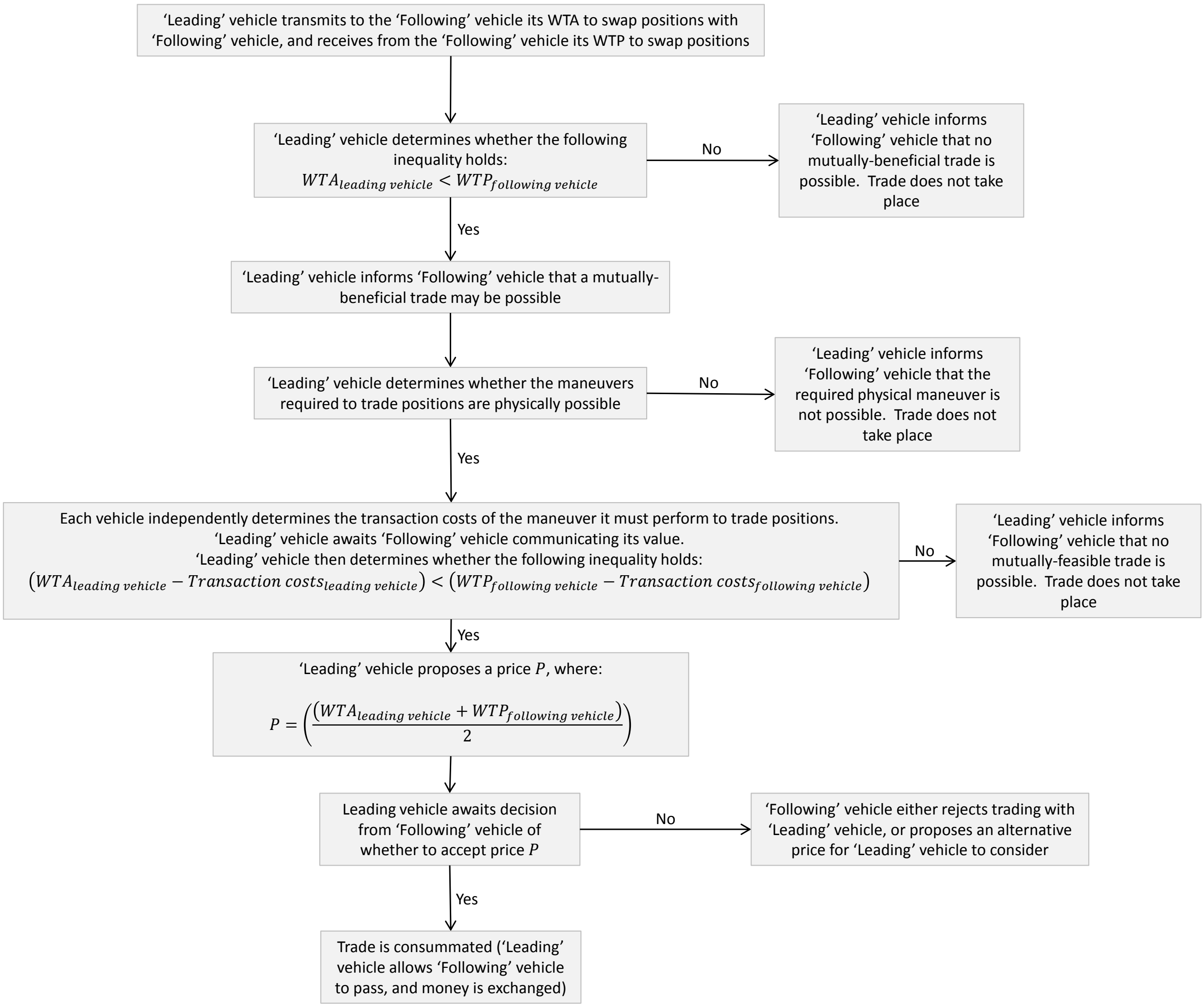

Figure 1: Flowchart summarizing a representative sequence of communications and actions (as described in the listing in Section 3) that may take place between a given pair of vehicles (one ‘leading’ and the other ‘following’) engaged in the prospective peer-to-peer marketplace, from the perspective of the ‘leading’ vehicle

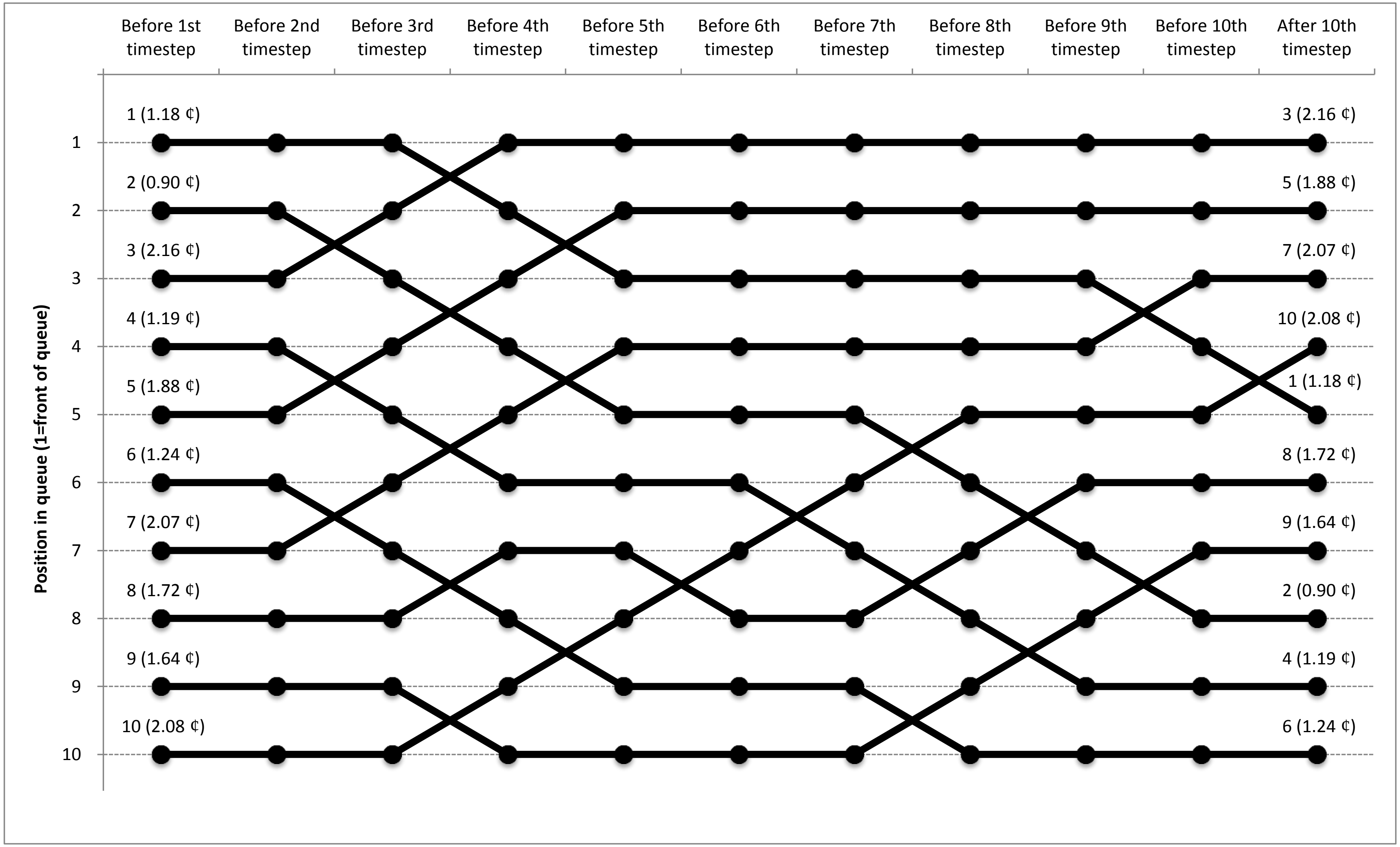

Figure 2: Vehicle positions in the traffic stream throughout the example run of the simulation (traffic stream of 10 vehicles). Labels shown at beginning and end of simulation are in the following format: Vehicle ID number (WTP in cents per position in traffic stream)

	Gross payments (absolute value) traded by vehicle in exchange for priority in traffic stream (absolute value of each	Net payments to/from other vehicles	Aggregate surplus from trading generated for each vehicle's occupants through exchanges to which it is a party (in units of generalized cost, manifested as *monetary payments* when selling and *position-in-traffic-stream* when buying)	Number of trades to which vehicle is a party	Number of delays involuntarily incurred due to downstream vehicles exchanging priority
Vehicle #1	6.47 ¢	6.47 ¢	0.48 ¢	4 (4 'buys' / 0 'sells')	0
Vehicle #2	8.48 ¢	8.48 ¢	1.80 ¢	6 (6 / 0)	4
Vehicle #3	3.18 ¢	-3.18 ¢	0.58 ¢	2 (0 / 2)	0
Vehicle #4	7.69 ¢	7.69 ¢	1.01 ¢	5 (5 / 0)	10
Vehicle #5	4.45 ¢	-4.45 ¢	0.74 ¢	3 (0 / 3)	2
Vehicle #6	6.26 ¢	6.26 ¢	0.74 ¢	4 (4 / 0)	16
Vehicle #7	6.42 ¢	-6.42 ¢	0.37 ¢	4 (0 / 4)	5
Vehicle #8	6.15 ¢	-2.33 ¢	0.85 ¢	4 (1 / 3)	12
Vehicle #9	5.99 ¢	-2.28 ¢	0.58 ¢	4 (1 / 3)	17
Vehicle #10	10.18 ¢	-10.18 ¢	1.27 ¢	6 (0 / 6)	10
Total (of example simulation run)	32.61 ¢ (sum of above values, divided by two as there are two parties to each trade)	0.00 ¢	8.43 ¢	21 (sum of above values, divided by two as there are two parties to each trade)	76
Total (averaged across 100 runs)	**40.31 ¢ (std. deviation: 5.01 ¢)**	**0.00 ¢ (in all runs)**	**9.63 ¢ (std. deviation: 1.54 ¢)**	**19.37 (std. deviation: 3.29)**	**37.04 (std. deviation: 14.01)**

Table 2: Vehicle-specific results from simulation analysis (traffic stream of 10 vehicles). Values in the final row are averaged across 100 runs of the simulation. All other values in the table are from the example run of the simulation.

	5th percentile	25th percentile	*50th percentile (median)*	75th percentile	95th percentile	**Mean value** (std. deviation in brackets)
Correlation coefficient (vehicles as units of analysis) between willingness-to-pay and position number in traffic stream (1 is front of traffic stream; 10 is last vehicle in traffic stream) at end of simulation (after time step #10)	-0.88	-0.77	*-0.62*	-0.40	-0.11	**-0.55** (-0.27)
Correlation coefficient (vehicles as units of analysis) between willingness-to-pay and net exchange of value (incomings minus outgoings)	-0.96	-0.84	*-0.76*	-0.66	-0.40	**-0.73** (-0.13)
Correlation coefficient (vehicles as units of analysis) between willingness-to-pay and number of delays involuntarily incurred due to downstream vehicles exchanging priority	-0.72	-0.51	*-0.27*	-0.07	0.27	**-0.27** (0.30)

Table 3: System-level results from 100 runs of the simulation analysis (traffic stream of 10 vehicles)

Inputs				Outputs			
Lower bound of distribution of Willingness-to-Pay/Accept	Upper bound of distribution of Willingness-to-Pay/Accept	Lower bound of distribution of transaction costs	Upper bound of distribution of transaction costs	Gross payments (absolute value) traded	Aggregate surplus from trading	Number of trades	Number of delays involuntarily incurred
0.75 ¢	1.5 ¢	0 ¢	1 ¢	85.57 ¢ (std. dev: 12.63 ¢)	14.78 ¢ (2.95 ¢)	84 (11)	1,926 (320)
0.75 ¢	2.25 ¢	0 ¢	1 ¢	279.50 ¢ (29.88 ¢)	71.72 ¢ (10.42 ¢)	186 (20)	4,839 (524)
0.75 ¢	5 ¢	0 ¢	1 ¢	1,069.62 ¢ (63.82 ¢)	384.93 ¢ (30.44 ¢)	372 (15)	9,534 (465)
0.75 ¢	10 ¢	0 ¢	1 ¢	2,206.72 ¢ (127.84 ¢)	883.74 ¢ (62.71 ¢)	408 (12)	10,549 (362)
0.75 ¢	25 ¢	0 ¢	1 ¢	5,415.02 ¢ (324.71 ¢)	2,343.83 ¢ (138.12 ¢)	421 (9)	10,847 (292)
0.75 ¢	1.5 ¢	0 ¢	2.5 ¢	29.58 ¢ (6.70 ¢)	4.94 ¢ (1.22 ¢)	26 (6)	673 (185)
0.75 ¢	2.25 ¢	0 ¢	2.5 ¢	87.92 ¢ (14.13 ¢)	22.36 ¢ (4.57 ¢)	59 (10)	1,513 (273)
0.75 ¢	5 ¢	0 ¢	2.5 ¢	613.04 ¢ (63.08 ¢)	231.94 ¢ (31.33 ¢)	213 (20)	5,441 (556)
0.75 ¢	10 ¢	0 ¢	2.5 ¢	1,938.51 ¢ (108.96 ¢)	816.40 ¢ (72.84 ¢)	359 (15)	9,349 (412)
0.75 ¢	25 ¢	0 ¢	2.5 ¢	5,322.26 ¢ (307.85 ¢)	2,343.36 ¢ (145.73 ¢)	411 (12)	10,572 (367)
0.75 ¢	1.5 ¢	0 ¢	5 ¢	14.08 ¢ (4.23 ¢)	2.37 ¢ (0.79 ¢)	13 (4)	322 (103)
0.75 ¢	2.25 ¢	0 ¢	5 ¢	41.04 ¢ (8.28 ¢)	10.36 ¢ (2.36 ¢)	27 (5)	715 (149)
0.75 ¢	5 ¢	0 ¢	5 ¢	252.92 ¢ (30.37 ¢)	96.64 ¢ (14.68 ¢)	89 (11)	2,245 (328)
0.75 ¢	10 ¢	0 ¢	5 ¢	1,261.68 ¢ (120.51 ¢)	558.68 ¢ (75.27 ¢)	235 (21)	6,088 (632)
0.75 ¢	25 ¢	0 ¢	5 ¢	4,929.10 ¢ (280.73 ¢)	2,239.58 ¢ (148.93	384 (13)	9,882 (411)

Table 4: System-level results from 100 runs of the simulation analysis (traffic stream of 100 vehicles)