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***Abstract*— This paper explores a new vision for urban and suburban transportation, termed Personalised Public Transportation, which builds upon recent trends in vehicle sharing, electric vehicles, mobile payments and cloud computing. The goal is to build on the best of the worlds of private and public transportation. Private transportation offers ownership, comfort and convenience, but is higher cost, and subject to externalities (traffic jams, pollution, etc.). Public transportation is efficient, cheaper and has lower energy/Carbon footprint, but has a last-mile problem (access) and low spatio-temporal coverage in suburbia. We envisage a future model of leasing public transportation via a service similar to cell-phone services, where the user pays for convenience and sharing of a network. We describe the key design features inherent to this mobility model. The vehicular platform allows the entire fleet to be operated and managed via a cloud computing service in order to maximise convenience and minimise cost. An optimisation formulation to quantify the benefits of Personalised Public Transportation shows that it is a promising approach for transforming future generations of transportation into sustainable ecosystems.**

I. INTRODUCTION

The population of cities around the world is growing rapidly. The World Health Organization notes that the majority of the world's population today lives in cities, and this proportion will increase considerably over the next few decades [1]. As boundaries of cities are stretched to accommodate the growing population, major challenges arise for maintaining a sustainable transportation infrastructure.

Broadly, there are two forms of transportation, private and public. Private transportation – predominantly personal cars – offers ownership, comfort and convenience. On the downside, cars incur high cost, both CAPEX and OPEX. The latter comprising insurance and registration costs, which are high, and costs for fuel, maintenance, parking, etc. In addition, private transportation is subject to peak road congestion; The Department of Transport and Regional Services of the Australian Government estimates the social costs of congestion in Australia to reach a staggering $20.4 billion by 2020 [2]. The use of personal cars also contributes significantly to greenhouse gas emissions [3].

Public transportation – predominantly trains – is efficient (carries more passengers simultaneously), low cost, reliable and has lower energy and Carbon footprint than private transportation [4]. However, it can have low spatio-temporal coverage in suburbia, and suffers from the last-mile problem, i.e. access to and from the train station is often not very convenient. These factors combined have resulted in people

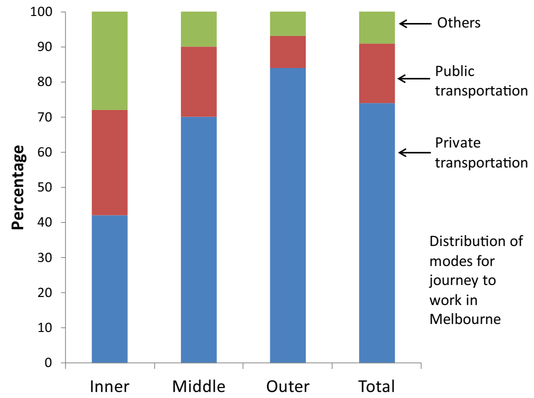

Fig. 1. Use of personal cars, i.e. private transportation, for journey to work increases with distance from inner Melbourne attributed largely to low spatio-temporal coverage of public transportation in the suburbia. The "Others" in the figure represents the fraction of people who work from home, walk or cycle to work. Similar trend is observed for other capital cities in Australia. Source: Analysis of Australian Census of Population and Housing 2011 place of usual residence.

choosing personal cars (in Australia) as the dominant mode of transport, as shown in Fig. 1.

Building on recent trends in vehicle sharing, in this paper we envision a new mobility model, termed **"Personalised Public Transportation"**, which offers the best of the worlds of private and public transportation, namely *convenience* like private transportation (with fewer externalities), and *cost* approaching public transportation. We believe that this mobility model, coupled with its key operational features, is a promising approach for transforming the transportation sector to be more sustainable.

The rest of this paper is organised as follows. In Section II, we give an overview of today's vehicle sharing schemes. We describe the Personalised Public Transportation Service in Section III. An analytical formulation to quantify some of the benefits of the proposed mobility model is developed in Section IV, and the results are presented in Section V. We conclude the paper in Section VI.

II. VEHICLE SHARING

A concept that is growing in popularity is vehicle sharing, of both bikes and cars. Examples of a few bike sharing services include New York City's CitiBike [5] and Melbourne Bike Share [6]. Zipcar [7] and Car2Go [8] are car sharing services, which are based in North America and Europe, while GoGet [9] and Flexicar [10] are based in Australia.

These services operate by providing access to a fleet of cars on an as-needed basis 24/7. The cars are distributed within a service zone and users reserve it for a specific duration. They are not explicitly charged for costs associated with maintenance, insurance, fuel, etc.

Vehicle sharing in general, and car sharing in particular, are positive initiatives in the direction towards sustainable transportation, as evidenced by statistics reported by the various service operators. For example, in Australia, every GoGet car takes 9 private cars off the road, and people on average drive 20% less after becoming a GoGet member [11]. Nevertheless, one of the major limitations of these services (as well as that of the bike share services) is that they usually have dense coverage in and around the city/downtown area, where users have alternate means of transportation such as trains and trams, but have little or no coverage in suburbia. This is shown in Fig. 2 for Melbourne. A consequence of this is that the 'last-mile' problem remains largely unsolved, which is important for mitigating some of the strains associated with private transportation.

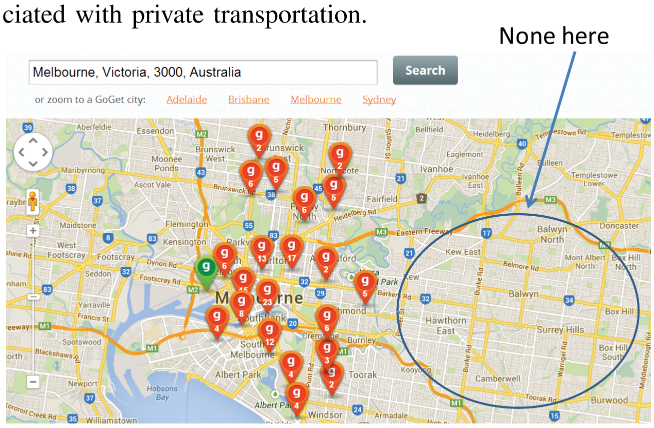

Fig. 2. Availability of GoGet shared cars in Melbourne is dense in and around downtown as indicated by the red and green icons. There is little or no coverage in suburbia.

Further, a majority of these services do not allow one-way trips, and require cars to be returned to a dedicated parking position[1] (usually from where it was picked up) [12]. There are financial implications for not doing so. Finally, their costs are not inexpensive compared to other car rentals or taxis (for certain usage patterns), and the cars cannot be kept at home overnight (for a small premium).

III. Personalised Public Transportation Service

Building on the idea of vehicle sharing, we envision Personalised Public Transportation Service (PPTS), a practical and efficient mobility model for future generations of transportation. PPTS allows leasing of vehicles using a service similar to cell-phone services, where the vehicle is "personalised", akin to the use of private cars, but can be "shared" across users at different points in space and time. The fleet of vehicles would be operated and managed via a cloud computing service, i.e. the vehicle is virtualised, analogous to computers, which are virtualised in a data centre like infrastructure, enabling cloud computing principles to be applied to transportation for efficiently managing the association or binding of users to vehicles so as to maximise convenience and minimise costs. In the context of PPTS, note that public transportation does not mean mass transport.

[1]Car2Go is relaxing this constraint.

A. *Key Features*

We now describe the key features and attributes of PPTS:

1. Superior coverage: First and foremost, PPTS is aimed at providing coverage in both urban and suburban regions. Positioning PPTS vehicles within walking distance of households would be highly attractive from the residents point of view. Further, as governments continue to make significant investments to augment the capacity and spatio-temporal coverage of the public transportation network (e.g. trains [13]), we believe that PPTS can be instrumental in mitigating the last-mile problem by encouraging residents to use PPTS as a means to get to the train stations, thereby enabling a large part of their journey to be made on public transport. Overcoming the last-mile problem, however, is not the only goal of PPTS, as discussed next.

2. Greater convenience: PPTS offers remarkable convenience and ease of use by being flexible in the policies governing vehicle pick ups and drop offs. Vehicles can be 'leased' and 'released' at any point in space and time. A distinguishing feature of PPTS compared to existing schemes is that vehicles can be kept at home overnight, if desired, for a small premium. Thus, PPTS vehicles could be available at the doorstep. Users will have the option to undertake one way trips, in addition to making round trips. Vehicle reservations can be made on the web or via intelligent smartphone apps. These attributes ensure that any 'anxiety' effect when it comes to the availability of vehicles will be eliminated, thus providing on par or better convenience than traditional vehicle sharing schemes.

3. Multimodal fleet of electric vehicles (EVs): Existing vehicle sharing schemes are, for the best part unimodal, meaning they are either bike sharing schemes or car sharing schemes. PPTS will encompass multimodal vehicles, i.e. 2-, 3- and 4-wheelers, as shown in Fig. 3. We will call these vehicles E-Bikes, E-Scooters and E-Cars respectively. Furthermore, PPTS will employ small form-factor vehicles. This notion is not outlandish, as exemplified by cars such as Renault Twizy [14], Nissan Land Glider [15], and Google's autonomous car [16].

Our motivation for choosing small form-factor vehicles is the following: (1) Their energy footprint is considerably lower than regular cars. For example, the 4-wheeler Nissan Land Glider has 1/2 the frontal area and 1/2 the drag coefficient of a regular car, meaning it uses only 1/4 of the energy [17], making a compelling case for adopting such vehicles for environmental sustainability. (2) The small size allows the existing road infrastructure to be used more efficiently by allowing lanes to be shared with other similar vehicles. This significantly reduces expenditure for augmenting road infrastructure such as for adding lanes to

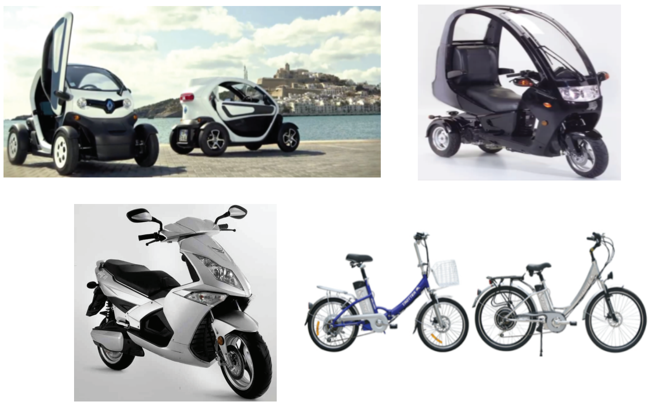

Fig. 3. Multi-modal fleet of electric vehicles envisioned by the Personalised Public Transportation Service comprising 2- (E-Bike), 3- (E-Scooter) and 4-wheelers (E-Cars).

cater to more cars. (3) For the same real estate, parking lots can now accommodate more cars, thereby reducing the investment needed for upgrading parking facilities. (4) Travel times can be cut substantially, up to 50% by some estimates [18]. Our reasons for using EVs are described next.

4. Compelling pricing: PPTS vehicles can be leased and released using plans similar to cell-phone services. We envisage two types of pricing structures – subscription-based and pay-as-you-go-plans. The former permits daily, weekly, monthly or yearly subscription. Subscription for an E-Scooter allows the use of all E-Bikes in the fleet, for example when an E-Scooter is not desired or unavailable. Similarly, subscription for an E-Car allows the use of E-Bikes and E-Scooters. Pay-as-you-go plans employ per-minute or per-hour pricing with access to vehicles similar to that of subscription-based plans. An adequately sized multimodal fleet therefore provides flexibility in the choice of vehicles and empowers competitive pricing to be offered to customers.

Another aspect contributing to compelling pricing is EVs, which can substantially cut operational expenses given the soaring petrol costs. Studies have shown that the cost per km of an (retrofitted) EV in cities is $\approx$ 2 cents/km, while a petrol car incurs $\approx$ 12 c/km [19]. We expect the cost per km of small form-factor EVs to be even lower. Further, they incur lower maintenance costs as well due to fewer mechanical parts. Economies of scale and falling Li-Ion battery prices [20] will accelerate the reduction of capital costs. These factors in conjunction with real-time vehicle tracking and analytics, robust optimisation techniques and proactive user incentives (e.g. to drop vehicles off at charging stations) will assist in lowering repositioning costs of the vehicles, which is known to be high.

5. Efficient fleet management: As mentioned earlier, PPTS applies cloud computing principles – i.e. managing the association of users to shared resources such as virtual machines in data centres, which has proven to be extremely efficient – for managing the association of users to vehicles. This can be done to maximise societal benefits, such as mitigating road congestion, minimising contention for parking spots at vehicle charging stations/malls, maximising the use of public transportation when feasible, etc. This platform also gives the ability to explore the role of predictive analytics given the usage patterns so as to maximise convenience and minimise costs.

6. Generations of PPTS: The first generation of PPTS will comprise a multimodal fleet of small form-factor EVs, as described above. There is growing interest in autonomous cars as witnessed by a number of manufacturers (BMW, GM, Mercedes-Benz, etc.) testing various driverless prototypes [21]. Google has recently announced an autonomous EV car that does not have a steering wheel [16]. Several states in the US have already passed legislation that allows driverless cars to share the roads. As these vehicles gain traction, future generations (second, third, ...) of PPTS will incorporate them into their fleet. These vehicles can drive themselves to the doorstep of customers as and when a reservation is made, thereby dramatically enhancing convenience. In addition, no parking is required at the destination. The costs associated with repositioning the vehicles will be slashed owing to the absence of human involvement. Autonomous vehicles are game-changing trends, which will be embraced by PPTS to boost the value proposition of the service. Optionally, generation zero of PPTS will rely on petrol-based smart cars such as Daimler's Fortwo [22].

IV. An Optimisation Model for Quantifying the Benefits of PPTS

We now develop a *macro-level* multi-commodity capacitated flow model to evaluate the benefits of the Personalised Public Transportation Service. While more sophisticated and larger scale models such as the system-optimal dynamic traffic assignment [23] have been studied, our intention here is to get a first-order insight into the benefits of PPTS. To this end, we describe the formulation below.

Consider the simple three node network shown in Fig. 4. The triangular nodes in the figure are the origin/destination of traffic demands (for e.g. city suburbs), while the arcs represent the roads interconnecting the suburbs. We quantify the benefits of PPTS relative to the dominant mode of transportation today, namely regular private cars, using three metrics – travel cost, energy footprint and Carbon footprint. For illustrative purposes, we assume that PPTS is unimodal, i.e. it only has cars with half the foot-print of private cars. Our formulation, though, is generic and models the multimodal version of PPTS.

We incorporate PPTS in the network shown in Fig. 4 by using an augmented network as shown in Fig. 5. This network $G(\mathbf{N}, \mathbf{A})$, where $\mathbf{N}$ and $\mathbf{A}$ are the sets of nodes and arcs, consists of three node types – the origin/destination demand nodes (denoted by triangles, same as Fig. 4), and two nodes each attached to the demand nodes, which represent transport Mode 1 (denoted by squares), namely private cars, and transport Mode 2 (denoted by circles), namely PPTS cars, respectively. The augmented network also consists of

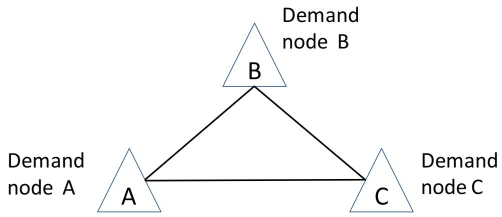

Fig. 4. A sample three node network comprising three demand nodes A, B and C, and roads interconnecting the demand nodes.

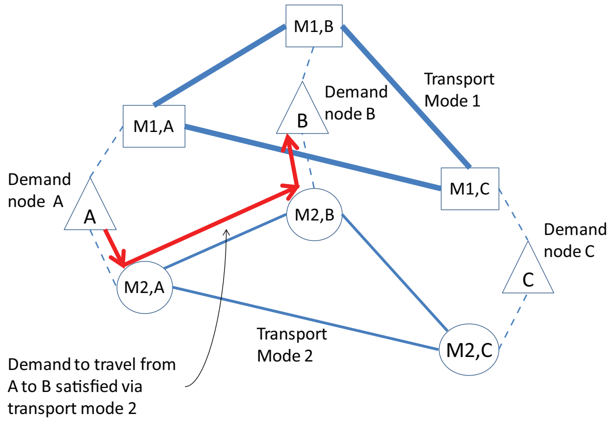

Fig. 5. The augmented network comprising three demand nodes (A, B and C) and two transport Modes, namely Mode 1 (private cars) and Mode 2 (PPTS cars).

three arc types – arcs that connect demand nodes and transport nodes (denoted by dashed lines), arcs interconnecting transport Mode 1 nodes (denoted by solid lines), and arcs interconnecting transport Mode 2 nodes (denoted by thin lines). In this example, if there is a travel demand from A to B, then a feasible route using PPTS could be $A \to (M2, A) \to (M2, B) \to B$, as shown in the figure. On the other hand, if there is a travel demand from A to C, then a feasible route using private cars could be $A \to (M1, A) \to (M1, B) \to (M1, C) \to C$.

Let $\mathbf{R}$ be the set of all travel requests. For each request $r \in \mathbf{R}$, we define a set of nodes, $\mathbf{N}_r \subseteq \mathbf{N}$, which request r can visit, and the set of arcs, $\mathbf{A}_r$, on which the request can flow. The demand for request r is given by D_{rij}, where $i, j \in \mathbf{N}$ and exactly one of the pairs of i-j is strictly positive (the others are zero), i.e. each request is a demand to travel exactly one origin-destination pair. The cost of one unit flow of request $r \in \mathbf{R}$ along arc $(i, j) \in \mathbf{A}_r$ is given by C_{rij}.

Since a PPTS car shares the same physical road as a private car but is half the size of a private car, the per unit consumption of Mode 2 on an arc in Fig. 4 is half that of Mode 1. We capture this notion in our model via the definition of an arc capacity L_{ij}, and a consumption factor α_{ruvij}, as defined below.

For an arc $(i, j) \in \mathbf{A}$, its capacity L_{ij} is the maximum number of vehicles (of the Mode represented by the arc) that can flow on that arc. The parameter α_{ruvij} is the amount of arc $(i, j) \in \mathbf{A}$'s capacity consumed by one unit of request $r \in \mathbf{R}$ travelling along arc $(u, v) \in \mathbf{Q}_{ij}$, where the set $\mathbf{Q}_{ij} \subseteq \mathbf{A}_r$ is the set of arcs $(i, j) \in \mathbf{A}$ that represents the same physical road arc in the unaugmented network.

For this multi-commodity capacitated flow model, let the decision variable f_{rij} be the flow amount of request $r \in \mathbf{R}$ on arc $(i, j) \in \mathbf{A}_r$. The linear program to minimise the total travel cost of travel requests is formulated below:

$$\min \sum_{r \in \mathbf{R}} \sum_{(i,j) \in \mathbf{A}_r} C_{rij} f_{rij} \tag{1}$$

s.t.

- Flow balance constraints for each request and node:

$$\sum_{i \in \mathbf{N}} f_{rij} + \sum_{i \in \mathbf{N}} D_{rji} = \sum_{i \in \mathbf{N}} f_{rji} + \sum_{i \in \mathbf{N}} D_{rij}, \quad \forall r \in \mathbf{R},\ j \in \mathbf{N}_r \tag{2}$$

- Flow capacity constraints:

$$\sum_{r \in \mathbf{R}} \sum_{(u,v) \in \mathbf{Q}_{ij}} \alpha_{ruvij} f_{ruv} \leq L_{ij}, \qquad \forall (i, j) \in \mathbf{A} \tag{3}$$

- Non-negativity constraints:

$$f_{rij} \geq 0, \qquad \forall r \in \mathbf{R},\ (i, j) \in \mathbf{A}_r \tag{4}$$

The above objective function is a *simplistic* representation of travel behaviour. The solution obtained here is considered to be ‘system optimal’, since optimal decisions are made at a ‘system’ level. The model can be used to carry out quick evaluation of the benefits, if any, of introducing new forms of transport into the network. For example, it helps answer the following questions: How can the benefit of trips with small cars be measured? How can travel requests be optimally distributed using a multimodal set of vehicles, etc.?

One could argue that the benefits of introducing a new form of transport can be evaluated based on travel survey data. But travel survey data is only a sample of the population's travel, and does not reflect the demand volume. Even if the benefits can be inferred via the sample of population's travel, it is not clear how one would select a trip to adopt a new transport mode. The multi-commodity capacitated flow model presented here overcomes this barrier by providing a system-view cost-optimal selection.

It is without doubt that the model presented here can be improved. Including practicalities such as a more sophisticated transport mode-choice selection is a prospective extension, but will imply trading faster computation for accuracy. Coupling the model presented here with a traffic simulation model is also an avenue for further research.

V. Numerical Results

The benefits of PPTS will be evaluated for metropolitan Melbourne shown in Fig. 6 under a peak morning traffic condition. Metropolitan Melbourne has a population of $\approx$ 4 million and there are thirty one Local Government Areas (LGAs). An LGA is a collection of suburbs, as shown by the circles in the figure. The arcs represent the primary connections (roads) interconnecting the LGAs. The peak morning (7am to 9am) traffic of more than 800,000 car trips puts immense pressure on Melbourne's tollways, freeways and main arterial roads.

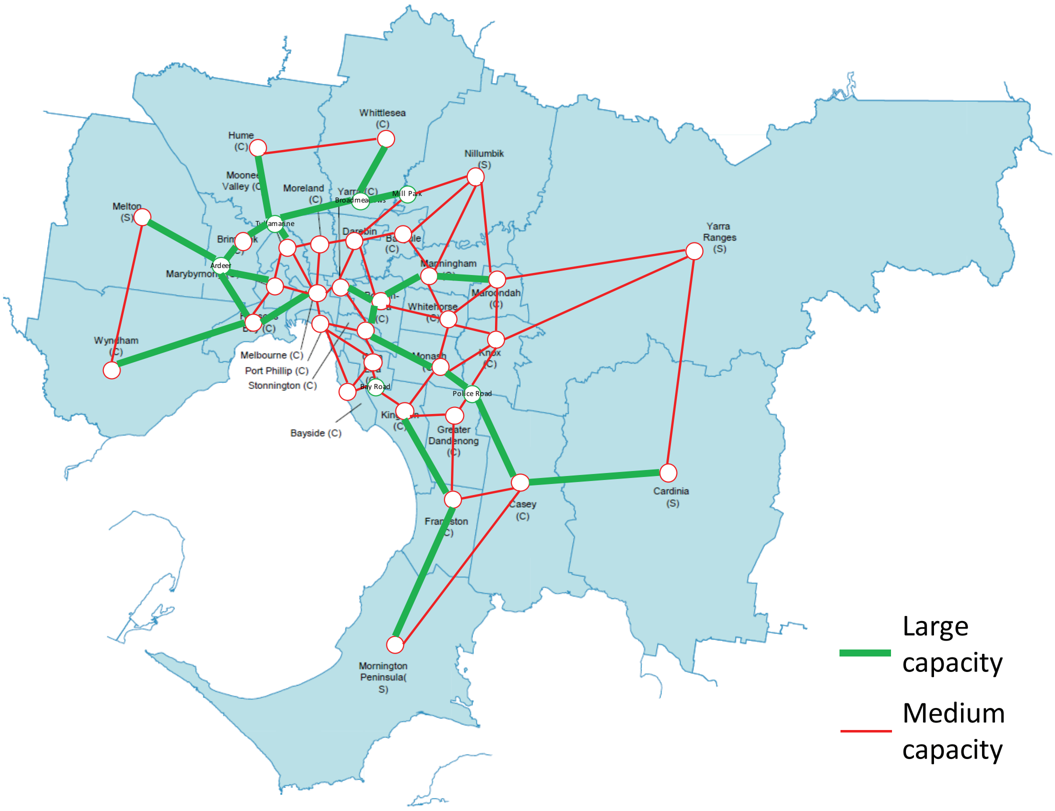

Fig. 6. Local Government Areas (LGAs) and primary connections between LGAs of metropolitan Melbourne, Victoria, Australia.

The origin-destination travel demand data for the purposes of this study is sourced from the Victoria Integrated Survey of Travel and Activity (VISTA) database [24], and demand modelling commissioned by the Department of Transport. Detailed input data is not presented in this paper for confidentiality reasons, but may be provided upon request.

We demonstrate the benefits (cost, energy footprint, and CO_2 emissions) of PPTS via a series of evolutionary phases of travel behaviour, described as follows:

- Phase 1: Trips made using regular cars (e.g. Mazda 3).
- Phase 2: Trips made using Daimler-Benz's SMART Fortwo smart cars.
- Phase 3: Subscription to use SMART Fortwo via PPTS (this is Gen 0 of PPTS), and
- Phase 4: Subscription to EVs (e.g. Renault Twizy) via PPTS (this is Gen 1 of PPTS).

These progressive phases help demonstrate the transitional benefits arising from: owning a regular private car to owning a small footprint car, car ownership culture in general to a subscription-based culture envisioned by PPTS, and using non-EVs to using EVs within PPTS.

For phases 1 and 2, parameters factored into the calculation of travel costs (i.e. C_{rij}'s) include the purchase, registration, maintenance, insurance and fuel costs of the car. These values are obtained from the manufacturers' websites as well as RACV, a popular car insurance company in Melbourne [25]. Travel costs for phases 3 and 4 are derived from estimates of the annual subscription fee and fuel cost of PPTS for Gen 0. We note that the energy footprint and CO_2 emissions for a regular car are 60 kWh/100 km and 0.19 kg/km, for SMART Fortwo, the quantities are 30 kWh/100km and 0.1 kg/km, and for an EV, they are 22 kWh/100 km and 0.08 kg/km. These values are obtained from [22], [26], [27], [28].

Table I summarizes the benefits (savings) of each evolutionary phase for 5% and 10% adoption percentages. The benefits are relative to all trips made using private cars (the dominant mode today). The adoption percentages are introduced by specifying an additional constraint in the multi-commodity capacitated flow model developed in Section IV.

It can be seen from Table I that the travel cost decreases as people behaviour moves from phase 1 to phase 4, since smart cars and PPTS with EVs cost less per km than regular cars. Total savings of 4.6% can be obtained for a *single* morning peak trip if 5% of users migrate to PPTS with EVs. This increases to 8.5% with 10% adoption rate. Significant savings in energy and Carbon footprint can also be realised for a *single* trip, as shown in the table.

To put these percentages into perspective and give the reader a sense of the annual savings in terms of the monetary benefits, we note from RACV's estimate that the weekly cost for using a regular car (e.g. Mazda 3) is $\approx$ \$170 [29]. The cost per trip therefore is \$17 assuming an average user makes 10 trips a week (2 trips per weekday). The 4.6% cost saving due to even 5% of users adopting PPTS with EV over the 800,000 trips per day and 48 weeks per year translates to hundreds of millions of dollars per annum. The corresponding energy savings is in the order of hundreds of GWh per annum, and the total reduction in Carbon footprint is in the hundreds of Megatonnes per annum.

TABLE I

SAVINGS ARISING FROM 5% AND 10% ADOPTION OF DIFFERENT TRAVEL CHOICES.

5% adoption of different services	100% private cars	95% private cars + 5% Smart cars	95% private cars + 5% smart cars via PPTS	95% private cars + 5% EVs via PPTS
Total cost	0	2.7%	3.5%	4.6%
Energy footprint	0	2.5%	2.5%	3.2%
CO_2 footprint	0	7.5%	7.5%	8.8%

(a) Savings due to 5% adoption of each transport phase w.r.t 100% ownership of private cars.

10% adoption of different services	100% private cars	90% private cars + 10% Smart cars	90% private cars + 10% smart cars via PPTS	90% private cars + 10% EVs via PPTS
Total cost	0	4.9%	6.4%	8.5%
Energy footprint	0	5.0%	5.0%	6.4%
CO_2 footprint	0	13.1%	13.1%	15.4%

(b) Savings due to 10% adoption of each transport phase w.r.t 100% ownership of private cars.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a new mobility model for urban and suburban transportation called Personalised Public Transportation Service. Building on recent trends in vehicle sharing, the mobility model targets convenience like private transportation with costs approaching that of public transportation. We described its key features, namely superior coverage, the use of small form-factor electric vehicles, cellphone like subscription plans, and efficient fleet management using cloud computing principles. We developed an optimisation model to obtain first-order insights into the benefits of PPTS using cost, energy and Carbon footprint as metrics, with the results pointing to substantial savings. We believe that PPTS is a promising approach for enabling a sustainable transportation sector in the years to come.

As part of our future work, we are: (i) Enhancing the sophistication of the optimisation formulation, (ii) Quantifying the reduction in expenditure – for augmenting road infrastructure and parking lots – due to the introduction of PPTS, (iii) Incorporating PPTS within a simulation framework such as the SUMO and MATSIM traffic simulators, (iv) Launching a trial with several design principles to evaluate the efficacy of PPTS, and (v) Integrating the concept of a demand-response transport system developed by one of the co-authors of this paper [30] into PPTS.

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