



Title	Flexible mobility in the smart city: the role of small personal electric vehicles
Authors(s)	Cuffe, Paul
Publication date	2018-04-12
Publication information	Cuffe, Paul. "Flexible Mobility in the Smart City: The Role of Small Personal Electric Vehicles." Springer, 2018.
Conference details	DIT – eseia Conference on Smart Energy Systems in Cities and Regions, Dublin, Ireland, 10-12 April 2018
Publisher	Springer
Item record/more information	http://hdl.handle.net/10197/9938

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Flexible mobility in the smart city: the role of small personal electric vehicles

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Abstract: A new class of personal vehicles, sometimes called *ridables*, has recently attained a level of technical maturity. These electric vehicle are light, portable and suitable for transporting an individual person in an urban environment. As batteries become increasingly affordable and energy dense, the range and capabilities of these vehicles are correspondingly enhanced. Notably, many *ridables* are suitable for intermodal commuting, as they are typically small enough to be brought along on a bus, train or tram. As such, this new class of vehicles seems to offer particular value for urban commuters, though this emerging use case has not been widely discussed in the extant literature. The present work seeks to provide a brief survey of the capabilities of the relevant vehicles, and to discuss some initial loose estimates for the portion of urban commuters for which they may be useful. Tentative suggestions for city planners and policy makers are offered to stimulate a discourse on how the capabilities of these vehicles can best be harnessed to foster sustainable and inclusive cities.

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1 Introduction

Ongoing advances in affordable power electronics (such as [1]), lithium ion batteries [2], permanent magnet synchronous motors [3], and gyroscopic sensors have permitted the emergence, and enthusiastic initial uptake [4], of a plethora of new portable, personal electric vehicles [5], [6], sometimes called *rideables* [7]. For instance, vehicle such as motorised skateboards [8], scooters [9] and self-balancing unicycles [10] are each seeing increasing commercial success. Commenting on personal electric vehicles in 2005, Ulrich [5] could legitimately observe that “*the full potential of the category has not been realized, to a large extent because the vehicles are not yet light enough, do not go far enough, and cost too much*”

The present work contends that, in the intervening years, each of these limitations – weight, range and cost – have been addressed, and, accordingly, these vehicles are now poised to realise their “*full potential*” as enablers of cost effective and energy-efficient personal mobility in urban environments. A key enabler of this upgrade in capabilities is the emergence of affordable lithium ion batteries: for instance, work in [2] demonstrated how lithium ion battery prices declined sharply over the period from 2005 to 2015, with the cost of one kW.hr of energy storage declining from approximately \$1300 to \$400 over that decade. Incremental yearly gains in battery chemistry have accumulated, so that costs and energy densities are now sufficient to underpin a new generation of affordable personal transportation devices.

This paper will take its cue from [11], which recently commented “*it is still unclear what kinds of established forms of transport [ridables] will replace and what new kinds of transport they will contribute to.*” The present work seeks to address this uncertainty, and will articulate how the ability of *ridables* to augment existing public transport offerings represents one of their unique distinguishing features. The synergies between these vehicles and existing public transport infrastructure will be a key theme addressed, as these devices are uniquely well suited to addressing the first- and last-mile problems for commuters.

Three vehicle categories were considered in [5]: “*Stand-on scooter*”, “*Sit-on cycles*” and “*Mobility scooters*”. In his concluding comments about these early *ridables*, Ulrich stated: “*suppliers have not yet arrived at a set of practical vehicles that best match technical feasibility and consumer demand*”

The present work contends that, since then, the various suppliers have risen to this challenge, with exciting new vehicle categories such as the previously-mentioned electric skateboards, self-balancing unicycles & dicycles eliciting growing consumer uptake in this segment. These vehicles sit within a paradigm of *flexible mobility*, where digital technologies such as ride hailing apps and bikeshare services are displacing the need for private car ownership in dense urban areas. Commenting on this trend, the authors of [12] noted: *“There is a strong indication that the close link of modernity and private car use is beginning to dissolve, and new attitudes towards urban mobility that make use of variable modes of transportation are evolving”*

To provide the groundwork for this vision of flexible mobility, the present paper will survey the capabilities of the currently available rideables. Within this survey, the characteristic strengths and weaknesses of each vehicle type will be articulated. A key contribution of the work will be an attempt to quantify the value proposition for these technologies, by estimating the available scope for daily time and cost savings using existing data on commuting modalities.

The work will conclude with suggested recommendations for urban planners and policy makers, to contribute to the emerging conversation on how these vehicles can be embraced to lessen car dependence in increasingly smart cities.

2 Available rideable devices

TABLE 1: EXAMPLES OF DIFFERENT PERSONAL ELECTRIC VEHICLES

<p>Electric bicycles</p> 	<p>Electric kick scooter</p>  <p>Credit: razor.com CC4.0</p>	<p>Mobility scooter</p>  <p>Credit: pngimg.com CC4.0</p>
<p>Electric skateboards</p> 	<p>Electric unicycle</p> 	<p>Diwheels</p>  <p>Credit: soarboards.com CC2.0</p>

A variety of different personal transporters which exploit powerful motors and energy dense batteries are available: a visual summary, including both new rideables and more traditional options, is provided in table 1. Rideables typically weigh around 10 kg, have motor powers rated up to a few kW, and are equipped with lithium ion batteries with capacities of perhaps a few hundred W.hr. Costs for rideables devices are modest, between perhaps \$300 and \$2000. Charge times are on the order of a few hours. With these specifications, ranges of ten to twenty kilometres between charges are typical. For many commuters, this range will obviate the need for a mid-day charge at their workplace, as an at-home overnight charge will suffice for both legs of their commute.

Most rideables are quite user friendly for an adult with reasonable balance, and can be mastered with just a few days of practice. Being electrical vehicles, they don't produce noise pollution nor do they harm air quality, and their modest energy usage can be sourced from sustainable sources.

Some specific notes on the emerging broad categories of rideables are provided below:

2.1 Electric skateboards

The idea of motorised skateboard has quite a long history: for instance, the gasoline-powered *MotoBoard* [13] emerged from California in the mid 1970s. More recently, the electrification of the same concept [14] has been popularised by another successful Californian company, *Boosted*. A typical electric skateboard is built on a flexible longboard deck for stability and ride quality, and powers one, two or even all four wheels with compact permanent magnet synchronous motors. These motors can either be integrated into the wheels themselves, or can transmit their power using synchronous belting. User acceleration and braking control is typically by a wireless hand-held remote, though control by foot-pressure sensing is also emerging as an option [15]. Steering is achieved by shifting ones body-weight.

Particular strengths of the electric skateboard are its inherent stability and enjoyable ride dynamics. However, the typically small wheels of electric skateboards are not well suited to uneven ground and changes of level (e.g curbs cuts), and its turning circle can be quite large. It is quite portable, though many boards are fairly long and not especially ergonomic. Folding boards have been proposed to improve portability.

2.2 Electric kick scooters

These scooters are typically designed with a flat deck on which the user stands, having two medium-sized wheels mounted fore and aft, and a upstanding frontal column with handlebars for steering and rider support. While powered scooters have existed for many years, electric devices are more recent [16], [17]. Options with larger wheels, or two frontal wheels, are available for more challenging terrain. Foldable devices also exist to enhance portability.

Benefits of electric scooters include their easy learning curve, direct steering control, good manoeuvrability and a reassuring sense of stability, due to handlebars. However, like the skateboard, their small wheels means that uneven terrain can present a challenge.

2.3 Self-balancing devices: diwheels and unicycles

This class of self-balancing vehicles lacks inherent stability: they maintain an upright orientation by controlling their motors based on high-frequency sampling of gyroscopic sensors. For instance, a forward tilt is counteracted by an increase in the motor's accelerating torque, which maintains the device's pitch orientation. The *Segway* was the first consumer offering to implement this control scheme [18]. Recent innovations have used a equivalent control scheme but on cheaper, lighter and more minimalist devices:

Diwheels (sometimes known as *hoverboards*): these resemble a Segway, with one wheel to left and to right, but they dispense with the upright rider support column and safety-oriented redundant hardware systems. Steering is achieved by shifting foot pressure to give differential speed commands to the motors on either side. This vehicle type was initially developed by the inventor Shane Chen [19] under the brandname *Hovertrax*. These devices were initially very popular, but were widely counterfeited [20], with \$4.8 billion worth of exports from China recorded in 2015 alone [21]. Notably, Chen himself is not optimistic on the capabilities of diwheels as a serious transportation device [20]: "*to me is just a toy. [...] It's fun. But you cannot use it for transportation. It's not practical*" Epidemiological work [22] has addressed the injury profile attending the early surge in popularity of diwheels, and has noted: "*safety equipment, such as wrist guards and helmets, should be worn in an attempt to reduce the number*

of injuries” Drawbacks to the typical diwheel design are its lack of inherent stability, small wheels, and somewhat awkward form factor. Benefits include its tight turning circle and gentle learning curve.

Unicycles: these also use self-balancing motor control, but power just one large, central pneumatic wheel, which the rider straddles by standing on foldable foot platforms mounted on either side of the motor housing. Chen also played a role in the early development of these devices [23], in which he perceives more transport potential [20]. Electric unicycles typically have wheels with diameters between 14 and 18 inches. They are inherently quite portable, with newer models offering retractable trolley handles to allow them to be wheeled along when not in active use. A core strength of electric unicycles is their ability to handle rough and uneven ground: this is because they have the largest wheel diameter of any ridables. Steering, and the required lateral balancing, is provided by the user shifting their body weight: this permits a tight turning circle. A key weakness of electric unicycles is their lack of inherent stability: for instance, electrical failures can cause a sudden and dangerous loss of pitch attitude. Starting and stopping is also awkward, as the user must dismount with one foot when not in motion. Good rider balance is required to operate these devices, and the learning process is perhaps not as rapid as for other ridables.

2.4 Other ridables

The above three categories are not exhaustive: for instance, exotic devices such as electric roller skates [24] and a hybrid skateboard/unicycle [25] have also been proposed. Ridables are an emerging technological category and it seems likely that innovation will continue in the sector. Future work may seek to develop a device that embodies the distinctive strengths of each of the extant types of ridables.

3 Scope for commuting time savings

In [26], 909 Texan women were asked to rate various daily activities in terms of positive emotions: the morning commute ranked least enjoyable, with the evening commute rated only marginally more agreeable. Generally speaking, commuting is an unpleasant and unproductive use of time. Shortening this burden, even marginally, could be of real value to workers, given how ubiquitous and recurrent the chore of commuting remains. Likewise, work in [27] has listed various activities that can make time spent commuting somewhat less unpleasant. They found *“dissatisfaction with the time spent commuting is a common experience; however, active travellers appear to be less dissatisfied with their commute than users of other modes.”* Ridables can be considered as a form of active travel, and using them may be enjoyable for some commuters.

As previously stated, the obvious target market for ridables is those whose commute include an awkwardly long walk. Indeed, only the most fortunate commuters both live and work adjacent to high quality public transport. As ridables are small enough to bring on even a city bus or a tram, public transport users across all modes are a potential user base. Those who use bikeshare schemes to complement public transport are a closely-related user segment.

3.1 Case study: travel patterns in UCD

University College Dublin is a reasonably large university whose main campus, Belfield, sits in the suburbs to the South of the city. An annual commuting survey [28] of staff and students gives some indication of travel patterns. Each day, approximately 30,000 people travel to campus: 26,500 students and 3,500 staff.

The modal breakdown in table 2 is provided as a rough basis on which to estimate the potential uptake of ridables. The rail commuters immediately suggest themselves: as the nearest rail stations are some kilometres from campus, anyone using this transport mode is inevitably faced with an awkward last mile journey.

The pedestrian segment is also addressable. As shown in table 3, 27% of walking commutes are of longer than a half hour duration: these journeys would seem logical candidates for substitution with the more rapid ridables. Likewise, 15% of cycle journeys take longer than half an hour: as these trips likely

cover a good geographic distance, a portion of these might be substitutable with some combination of rideables and public transport. As many bus stops are offered on the campus itself, a conservative addressability estimate of just 10% is offered for this segment.

Therefore, as a very rough figure, we might estimate that half of UCD’s rail users, one quarter of pedestrians, 15% of cyclists, 10% of cyclists and bus users and just 2% of car users might find value in adopting emerging rideables technology. These loose estimates of the addressable market in each segment are listed in table 2. These estimates indicate that perhaps 3,676 people, or 12.25% of the commuting population, may find value in using rideables technology.

Assuming that such a switch might save each person just ten minutes on each commuting leg, this represents a saving of 1,225 person hours each day. Monetising this using the prevailing minimum wage, this represents a time saving worth €11,334 every day, for the UCD community alone.

TABLE 2: MODAL BREAKDOWN OF UCD COMMUTERS [28]

Mode	Portion	Commuters	Addressable \approx	Users
Bus	38.2%	11,460	10%	1,146
Car (driver)	22.2%	6,645	2%	133
Cycle	20.5%	6,140	15%	921
Walk	11.3%	3,390	25%	848
Rail	4.1%	1,235	50%	618
Car (passenger)	1.9%	565	2%	11
Other	0.9%	272	0%	0
Motorcycle	0.6%	168	0%	0
				$\Sigma = 3,676$

TABLE 3: DURATION DISTRIBUTIONS OF WALKING AND CYCLING COMMUTES

	> 15 mins	15 \rightarrow 30	30 \rightarrow 45	45 \rightarrow 60	< 60 mins
Walking journeys	44%	29%	18%	8%	1%
Cycling journeys	45%	40%	12%	2%	1%

TABLE 4: MODAL BREAKDOWN OF DUBLIN COMMUTERS [29]

Mode	Portion	Commuters	Addressable \approx	Users
Car (driver)	44.6%	226,943	2%	4,539
Bus, minibus or coach	13.6%	69,202	10%	6,920
Walk	13.2%	67,167	25%	16,792
Train, DART or Luas	7.9%	40,199	10%	4,020
Cycle	7.6%	38,672	15%	5,801
Not stated	6.4%	32,566	-	-
Other (incl. lorry or van)	3.1%	15,774	-	-
Car (passenger)	2.7%	13,739	2%	275
Motorcycle or scooter	0.8%	4,071	-	-
				$\Sigma = 38,346$

3.2 Case study: travel patterns in the Dublin region

Some statistics on public transport usage patterns in the Dublin region in 2016 are provided in [29], and these figures are presented in table 4. Using a similar approximated addressability analysis as in table 2, estimates of the potential rideables usership can be offered. Note that here, just 10% of the rail ridership is considered addressable, as distinct from the 50% previously given, which was predicated on UCD's inherent remoteness from this transport mode. Again assuming that rideables can save ten minutes per leg of commute, and monetising using the minimum wage, it appears that €118,233 worth of daily time savings are available in the Dublin area alone. Alternatively, we can consider the 260 days in a typical working year: these time savings represent a monetary equivalent of €801 for a commuter earning the minimum wage. Notably, this figure is similar to the current retail price of many rideables.

While these estimated figures are of course somewhat notional, they are presented to articulate the point that opened this section: even marginal savings in commuting time are of great value when aggregated across the many commuters in a city, and the many commutes in a working career.

4 Urban planning and policy implications

The case studies in the previous section should indicate the real value that rideables offer to individual commuters, and more widely, to cities they live and work in. Rideables can enhance the catchment area of public transport and may open transit offerings to a wider subset of commuters. This means that rideables can help to reduce car dependency in modern cities, which, for reasons of sustainability and livability, is a key goal of much urban planning policy [30], [31]. To kindle a conversation on the benefits of embracing rideables, some policy suggestions are offered below:

- The legal position on the usage of rideable should be clarified, or amended as necessary. In many jurisdictions, rideables could qualify as motor-propelled vehicles [32], and may be subject to the same legal treatment as automobile traffic. To encourage a shift away from car dependency, a light-touch legal approach could be taken. If taxation, insurance and licenses are required, this will detract from the “quick, cheap and convenient” offering that rideables represent. A consistent legal definition for rideables should be embraced, perhaps defining ‘Personal vehicle’ as those falling within certain maximum speed and weight limits. Suitable respective thresholds could be 30 km/ph and 10 kg. A permissive approach could be taken in legislating for this vehicle class, waiving taxation and registration obligations, and merely imposing simple age (perhaps 14 years?) and sobriety requirements for operators.
- Bicycle lanes should be redesignated as ‘Personal vehicle’ lanes. By combining bicycle and rideables traffic, these lanes could see more usage, which better justifies their capital cost. As with bicycles, inclement weather makes the use of rideables less pleasant, as they are also unenclosed vehicles. Cities with good climates, therefore, offer strong growth potential for this sector. Less fortunate cities should consider building weather protections, such as rain shelters and wind breaks, for ‘Personal vehicle’ lanes.
- Urban planning documents should no longer use language that implies that walking and cycling are the only alternatives to car use for personal transport. This is no longer a tenable dichotomy, as the new rideables technologies are opening up an intermediate class of vehicles. Signage in parks and other public spaces should make clear that users of rideables are welcome. Byelaws and ordinances should likewise reflect this shift.
- Bike share schemes could be extended to also include rideables, to offer users the most apt vehicle for their particular journey and to introduce a wider demographic to this technology. By offering a wider portfolio of vehicle types, the diverse mobility needs of different citizens can better be met.
- Theft is one problem that rideables users face. Here, their small size and convenient lightness works against them, making them an attractive target for thieves. While commuters may be able to stash their device within their workplace, there is a need for on-street parking facilities

if rideables are to facilitate shopping and other third space activities. The provision of secure lockers in public spaces may help to incentivise the broader uptake of rideables.

- Many cities have policy targets for bicycle and public transport usage rates [33]. Cities could likewise target a segment of commuters to adopt rideables – perhaps 5% would be attainable. Subsidies are often offered for electrical cars [34] – why not likewise subsidise smaller, less intrusive vehicles?
- Standardisation of charger connectors and facilities for small electrical vehicles would also be a useful step to encourage uptake. Emerging standards for dc charging, such as USB-C [35], could be embraced here. Ideally, standardised charging facilities could be provided as part of secure locker facilities, as well as on-board public transport.

5 Conclusions

An accumulation of incremental technical advances have facilitated the emergence of light, portable, stable and rapid personal transport devices. While some may perceive these rideables as being mere novelties, or a fad, the present paper has used two case studies to clearly articulate the real value proposition that they offer. Crucially, these rideables are compatible with public transport, and so address one of the key shortcomings of traditional bicycles. By ameliorating the last mile problem, rideables tangibly enhance the attractiveness of public transport, and this work has suggested various ways that urban planners and policy makers can grasp this nascent opportunity to reduce car dependence.

6 Acknowledgements

The author thanks Milo Cuffe and David McMullin for their contribution to some of the ideas discussed in this work.

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