Creating an Innovative Mobility Ecosystem for Urban Planning Areas

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Abstract Urban planning, infrastructure design, and mobility policy are up against a tough system-level challenge: the rapid adaptation of shared mobility. The new mobility is destabilizing the current auto-oriented transportation paradigm, and gradually moving toward a new mobility ecosystem. In order to capture the potential and create shared infrastructure, an innovative mobility planning model based on a scientific approach was developed to identify context-sensitive area solutions and the scaling of the proposed ecosystem for short- and long-term horizons. The aim of this model is to build capacities and competencies, enable municipal authority and system planners to quantify the scale and cost, and accurately model the potential impact and benefits of various innovative mobility strategies.

Keywords Innovative mobility ecosystem · City planning · Connected multimodal · Collaborative implementation

1 Introduction: A Mobility Megatrend

Rapid adaptation of sustainable mobility, particularly smart technology based on shared/on-demand service, is changing the current auto-oriented paradigm. Shifts in lifestyle, an engaging planning culture, demographic changes, and the rise of the concept of "Mobility-as-a-Service" [1] are paving the way for a new mobility ecosystem in urban multimodal planning while replacing the demand for traditional oversized, expensive, and complex physical infrastructure. These changes started to appear in public sector policies acknowledging shared mobility and smart

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technologies. However, innovative mobility planning in the public sector is struggling to adapt to the rapid advancement of the shared economy. With fragmented urban mobility management and lack of system wide assessment, a gap in collaboration in the planning process is developing as planners work to supply an appropriate level of vehicle infrastructure while adding a multimodal facility as an "extra feature." An imbalance is being created between the growing demand for sustainable mobility and the oversupply of vehicle assets. Absence of a natural balance is holding back change. Seamless multimodal mobility that adapts from "delivering transportation" to "delivering solutions" could unleash the full potential of the emerging innovative mobility model [2]. Recognizing the unprecedented growth of shared mobility systems in the last decade [3], a new innovative mobility master planning process is envisioned in this model. The process incorporates a quantitative mobility analysis and infrastructure assessment process, and addresses people-oriented needs while redesigning scarce public spaces and the mobility delivery system.

The rise of smart and connected mobility [4] along with prevailing social and economic changes have created dramatic structural and societal consequences to the current mobility model, culminating in direct conflicts and strains between public sector regulations and service providers. Around the world, city governments are increasingly facing pressure to change their current approach to public engagement and policymaking. Financial uncertainty in the public sector [3], declining road reinvestments [5], and potential annihilation of the traditional mobility industry are a new reality. Reallocation of public space [6] and parking [7] for efficient modes are facing steep challenges from traditional inefficient system entities. Intensifying remaining developable urban lands [8] and replacing surface parking spaces with infill developments [9] have emerged as leading city building strategies in the last decade to protect the last remaining green spaces. The breadth and depth of these changes herald the reshaping of public policy and the governance structure, introducing shared goals with service providers to form an approach toward greater efforts in global sustainability while striving for meaningful prosperity [10] and maintaining safe space within a city's operating boundary [11].

Despite equity and wage concerns and the potential threat to public transit and active transport, shared mobility brings social and economic benefits in addition to environmental gains. This includes providing access to those who cannot afford to own or operate a vehicle, providing opportunities for extra income using excess capacity, offering more choices and connections to public transit services [12], and reducing parking demand and decreasing traffic congestion intensity to free up land, allocating up to 20–30% of land for new shared mobility services [13, 14]. If innovative mobility policies and implementation strategies/incentives are developed around low-carbon mobility as a "core service," new technologies will bring sustainable benefits to the community, environment, and economic progress.

Despite growing attention to innovative mobility and continued progress in disruptive technology, there is a surprising dearth of literature or research on a quantitative mobility planning approach, practical public policymaking and, more specifically, the scalable impact on traditional mobility planning, management, and governance. Planning assessment models generally exclude shared mobility services. The aim of an innovative mobility planning process is to reinvent multimodal mobility assessment with innovative options and smart technologies. Recognizing the impact of shared mobility options on city policies and planning practices, the model reinforces the low-carbon option while addressing environmental and health benefits, and social equity in mobility planning for all users. Bringing shared mobility research findings into implementation tools and repurposing land and reallocating space to sustainable and shared mobility facilities, the innovative approach ensures new shared and connected technologies do not become just another platform of exclusion, and avoid the disproportionate burden vehicle throughput placed on unban quality of life.

2 Developing a Framework for the Mobility Ecosystem Model

Driven by the prospects of disruptive innovation, future mobility planning will improve the quality of life of its residents by forging a positive relationship between technology, business and the environment [15]. The new mobility model will assess, measure, and integrate every possible element of the mobility ecosystem. To achieve this objective, the development of this model incorporates several pioneer and recent concepts in mobility system and city building approaches. The conceptual mobility ecosystem framework was built on the premise that physical space constraints and economic and resource constraints will increasingly set the “safe operating limits” of a city’s carrying capacity, i.e., in recognition of the basic philosophy of “planetary boundary” [11, 16]. A Dutch model of Spatial Planning and Design [17] is reviewed and modified to reflect the complex layers of the ecosystem, the interrelation between modes of travel, and the fundamentals of the natural environment [18]. In order to capture the transformative power of new transportation technologies and social trends, the SMART model was envisioned to transform the automotive industry’s business toward sustainable transportation approach at multi-scale and dynamic coupled systems [19]. Finally, demand management strategy has become the focus of recent policy discussion [20]. Three fundamental strategies to reduce emissions from the transportation sector, collectively known as the Avoid-Shift-Improve approach [21], are gradually being commonly accepted due to the prospect of the impossibility of future road improvements satisfying unlimited traffic growth. Combining automotive and new mobility service integrators into a multimodal model, a set of basic principles associated with the limitations of mobility infrastructure and service was integrated into the mobility ecosystem model (Fig. 1).

Identifying future aspects of the symbiotic relationship between six fundamental interactive elements in a mobility ecosystem, the proposed innovative mobility planning model (see Fig. 2) envisions a novel urban morphology, shapes a new

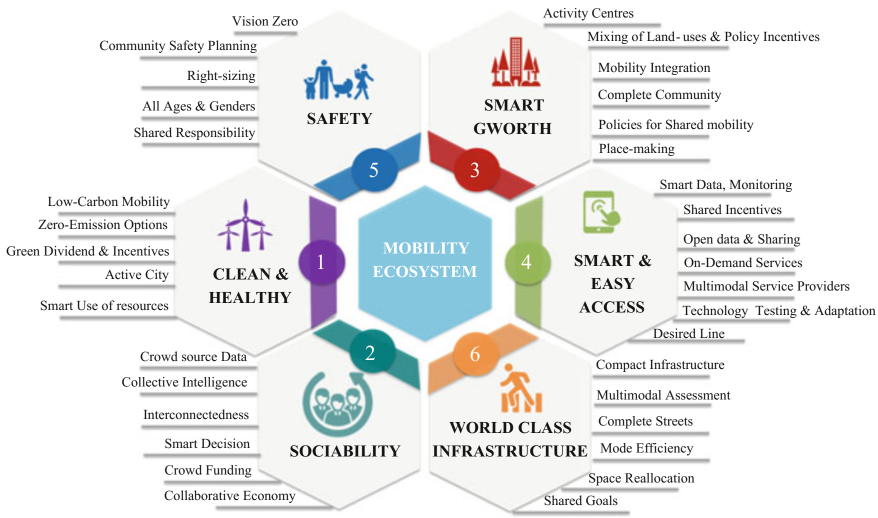

Fig. 1 Basic concepts of mobility ecosystem principles (adapted from Ohta [20])

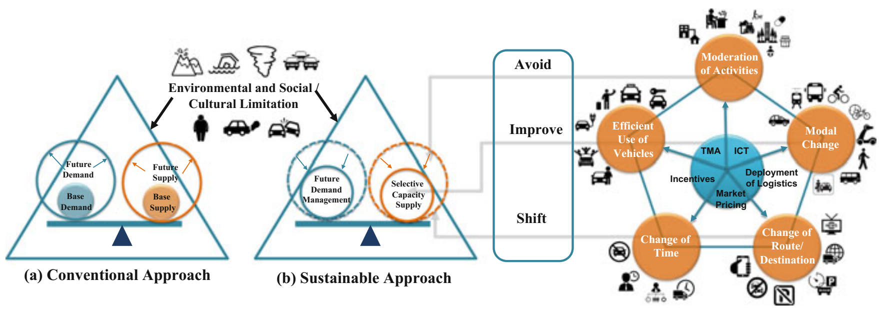

Fig. 2 Conceptual framework of innovative mobility ecosystem for urban planning areas

experience of urban space, and turns unexplored assets into an ecosystem of vibrant, sustainable innovation. The six fundamentals elements (and associated planning policies) of the mobility ecosystem are: (1) healthy environment, low-carbon footprint and clean energy; (2) smart growth principles linking the right mobility mix; (3) sociability and livability by enhancing social capital and innovation; (4) smart and easy access to all types of mobility services; (5) sustainable safety by reducing crash risk and severity; and (6) world class infrastructure that prioritizes sustainable and shared uses.

Through a rigorous literature review and background analysis, the following sections describe the development of the key principles, and the factors that limit each fundamental element and guide the implementation of smart technologies in the quantitative process of mobility planning.

2.1 *Clean and Healthy Cities: The Challenges of Urban Mobility and Smart City Building*

The demand for physical space for new human development generates driving alone commuting which comes with unused excess capacity and unsustainable use of limited natural resources. In spite of immense technological development and progress, our economies and societies still fundamentally depend on ecosystems to provide us with a hospitable climate, clean water, food, fibers and numerous other goods and services. Two planetary processes, fossil fuel emissions by private vehicles and auto-oriented sprawling land use, are gradually pushing the safe thresholds of "planetary boundaries" [11]. By 2050, urban mobility systems will use 17.3% of the planet's bio capacities, five times more than they did in 1990 [2]. Following this global trend, the transportation sector in the City of Toronto has grown exponentially to become the largest source of green-house-gas (GHG) emissions (41%, excluding rail, plane and boat) [22]. Linking mobility patterns and greenhouse gas emissions, a Greater Toronto Area study [23] concluded that most emissions are caused by "extreme commuters," people who work in the old City of Toronto, but live in the outer suburbs and commute by private vehicle. Thus, unlike last century's city planning, the focus of this new mobility model is to create a low-carbon "urban ecosystem" [17] by mixing land-use with appropriate density, addressing the depletion of natural and financial resources, and continuing to manage sustainable growth within "planetary boundaries" that will shift mobility patterns to achieve the target of GHG emissions.

2.2 *Sociability: Changing Socioeconomic Structure and Travel Patterns*

The emergence of a new social order and collaborative consumption is driving our society in exciting new directions for future mobility, and reshaping almost every aspect of society. The rise in the importance of "sociability" (instead of efficiency) and citizens' environmental preferences appear to be important drivers in the pursuit of specific emission measures and the adaption of climate plans [24].

Firstly, a new collaborative economy is disrupting the traditional ownership-based mobility paradigm. Highlighting the influence of a new model of organic economic growth and ecological necessity [10], evidence is emerging that beyond a certain point, growth does not increase human well-being and that the ultimate solution lies with new sustainable mobility investment policies (such as the rate of return on investment should be lower, around 1.5%) [25] to achieve "Our Common Future" [26]. New collaborations are emerging between political platforms and economists. These economic parameters and social changes are reflected in the proposed model in the estimation of life cycle assessment [27, 28], environmental benefits [29] and social impact to quantify urban livability.

Secondly, demographic changes have profound impact on urban mobility. For instance, roughly 60% people live and work within Toronto downtown. Single women have become an important share (roughly 30%) in the real estate market and most of them walk, cycle or use transit to daily destinations. A global trend of stagnated vehicle growth [31] is reflected in changing travel patterns. In Toronto, for instance, only half of people use a vehicle and over one-third use transit. Cycling (current mode share 2.2%) has emerged as the fastest growing of transportation modes (annual growth 7.5%) followed by walking (1.5%) [30]. As a result, vehicle mode share has been falling 0.5% annually while transit share has been increasing at same rate. These findings lay the foundation of a future modal share pattern that reduces the number and length of vehicle trips opening the door for appropriate density and diversity of land-use in urban centers and corridors.

Thirdly, facing a changing mobility landscape and affording people more choices, the automotive industry (Original Equipment Manufacturers, OEM) is forced to rethink the diversity in their business models and is gradually moving toward multimodal urban mobility solutions [32]. OEMs are introducing car sharing and ebike with a major focus on a “shared transit” system. Technology companies and new players are entering the market as service integrators. Reflecting the changes in the mobility industry, the proposed mobility model develops the capacity of all the possible elements using industry parameters to capture the appropriate level of local and technological context and determine an expected level of shared mobility usage.

Finally, the power of collaboration and sharing through digital technologies is helping to transform consumption pattern, design goods to last longer while reducing production, and move toward distributed, connected communities that will be control general people through peer trust [33]. Unprecedented global urbanization is recreating the city as economic center, giving rise to increasing online and immediate delivery services that replace the need for trips and lead to an increased number of shorter trips. These socioeconomic variables and consumption patterns are reflected in the proposed model as key indicators for estimating the scale of new mobility demand.

2.3 Smart Growth Principles Linking the Right Mobility Mix

Smart growth is a set of principles that promote more compact and mixed development, and create sustainable mobility. Smart growth reduces urban sprawl, parking demand and vehicle pollution, and maximizes the effectiveness of investment. Smart growth is often confused with ‘density’ and bad development, causing angst with local communities and local government. The reality is that when done well, with ‘appropriate’ density and mix, development based on smart growth principles can result in several economic, environmental and social benefits [34].

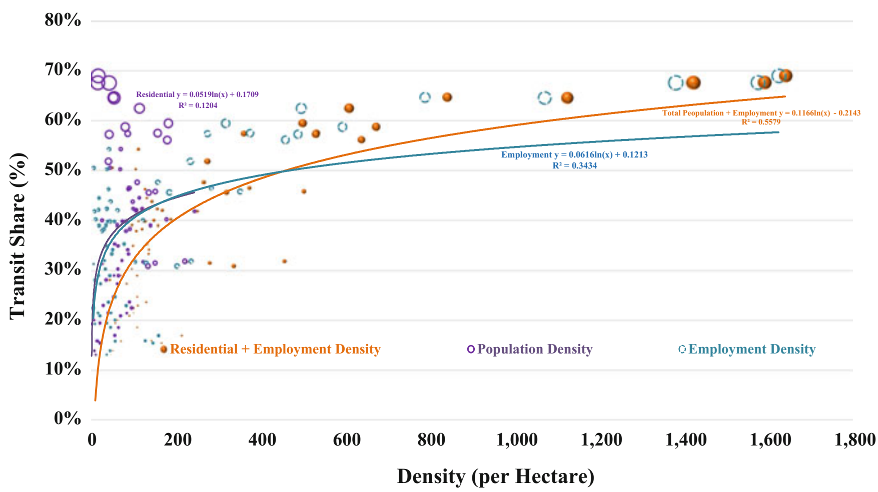

Fig. 3 Integration and limiting boundary of land use and transit relation [30]

The appropriate density varies with the area and overall context. In-depth analysis using Toronto data (within 500 m of subway stations) reveals benefits of density diminish beyond a "density sweet spot" [30]. While the minimum subway density threshold is usually 100 population and employment per hectare, the optimum transit share (i.e., 40–50% transit) is achieved when density is around 200–450. The downtown core, with a density exceeding 450, leads to a marginal increase in transit mode share (Fig. 3). While employment is the key ingredient of maximum transit usage, the appropriate share of diverse land-use (25–40%) is critical to providing access to daily needs. The reason behind low-performing subway stations (around 58%) are vehicle focus retail or employment usage, poor physical and digital connectivity or lack of real-time information, and pointed density around rapid transit stations [35]. Optimum limits of density also determine emission outcomes [36]. Total on-road CO_2 increases rapidly with population density below 1650 persons per square kilometer while per capita emissions decline as density rises (1650–3500 persons per square kilometer) and emissions begin to rise again as density exceeds 4000 persons per square kilometer. These boundaries set the limits of mode split, appropriate density, and the extent of diversity of land-use that maximizes self-contained trips.

The supply of parking, an intersection between mobility and land-use, entirely depends on minimum parking requirements that fail to account for complex relationships between parking supply and demand. Minimum parking requirements in cities are a likely cause of increased driving among residents and employees and higher cost of housing [37]. To the contrary, underground parking remains half empty whereas on-street parking is close to capacity in Toronto's major urban centers. This indicates a shift in land-use and changing demographics that prefer easily accessible parking spaces. Innovative mobility, particularly on-demand/shared systems, has profound implications for a city's parking requirements and may enable inhabitants to live without a car. Although municipalities update their parking requirement to reflect high-density uses, the impact of sustainable and shared mobility and market-based pricing on parking demand is largely unknown. This model aims to quantify the demand for space and parking of sustainable and technology users.

2.4 Smart and Easy Access

Unlike vehicle usage patterns, the effective use of sustainable and shared/on-demand modes depends on multiple layers of accessibility features. Firstly, pedestrian movement and social activities dictated by a '400 m rule' of pedestrian shed [38] and optimal street patterns with ideal connectivity [39] influence access time and shorten the distance to mobility service locations. Secondly, easy access from neighbourhoods through street networks to transit stops/station [40] and other service locations [41] optimize social benefits of mobility schemes. Thirdly, digital technologies with real-time information on trains, buses and on-demand/shared service availability can shrink the "reliability buffer" [42], the extra time a traveler builds into a trip to account for possible delays, and significantly reduce the "time window" improving quality of service. Research indicates that providing people with access to real-time transit information results in 15% less time spent waiting at bus stops [43], increases average daily ridership by 2% [44], and results in $5 million per year in additional fare revenue [45] with total potential savings up to $60B [15]. If transit wait time was eliminated using technology, the urban mobility score would be doubled [46]. The proposed model applies acceptable physical access distance, connectivity and access measures, and quality of service standards to redesign street network, minimize distances and optimize connections to sustainable and shared mobility service locations.

2.5 Safety in the Planning Process

Traffic safety plays a central role in increasing active transportation and connecting shared mobility modes to conventional public transit. However, traffic fatalities are traditionally framed as individual and mechanical failures rather than systematic flaws in mobility planning, urban and street design [47]. More recently though, a planning focused safety approach has emerged. In the 1980s, a Dutch safety model commonly known as the "sustainable safety traffic system" developed several quantitative targets to reduce the number and severity of collisions through better-integrated community and street planning [48]. Scandinavian and East Asian nations advanced the Dutch concept, treating collisions as a preventable disease.

Beneath these fundamental safety principles, evidence points to two root causes of traffic safety problems: longer driving distances per driver are a strong predictor of crashes [49]; and the combination of wider streets/intersections with wide lanes [50, 51] and unwarranted/unused right-turn lanes with an island [52] lead to higher number of crashes when higher proportion of seniors and greater number of sustainable and shared mobility users. Oversized infrastructure with higher design speeds tends to reduce interaction between street users and which ultimately increase collision risks [53]. Policies that work toward the systematic reduction of vehicle traffic while increasing pedestrian and cycling usage [54] and redistributing space and rescaling urban infrastructure [55] have emerged as important safety solutions. Recent "Complete Street" design approaches improve overall safety and create an opportunity for multimodal mobility [56]. The proposed model uses a scientific approach based on safety performance functions [57] to investigate the root cause of current safety issues. The model identifies several safety boundaries by using forecasts of multimodal trips and corresponding reduction of vehicle traffic due to shared mobility services, i.e., a combination of "sustainable safety" [48], nonlinear risk behavior [54] and "community safety planning" [58] concepts.

2.6 World Class Infrastructure

Best practices of sustainable mobility policies are currently shifting from the concept of "predict and provide" to "optimality and sustainability." Creating streets as places for trip destinations flows from the "Link" and "Place" concept [59, 60], and identifies context-sensitive land-use [61]. A detailed planning practice that unifies the role of different professionals and provides guidance in developing a comprehensive two-dimensional street classification has recently been developed such as 30 by 30 street downsizing strategy (30 kmph speed and 30 m right-of-way) that aligns with compact and dense city living ideas [60]. The world class infrastructure ideas in this model were developed from scientific evidence and creating street and intersections at all levels for safe human interaction. Traffic engineering solutions have kept adding lanes to reduce vehicle delays, but, limitations to capacity have to be recognized. Expanding intersections above a certain size has proven to be an expensive, ineffective and short-lived solution to traffic congestion problems [62]. Secondly, too many lanes lead to increased traffic volume, and increased distances traveled, leading to an increase in collision frequency [49, 57]. It is clear that road widening carries the seeds of a future decline in a city's livability. Thirdly, the system faces economic, political and environmental challenges including the question of an scale and size for transportation infrastructure [55]. Ignoring these challenges could lead to system failure if the system breaks down due to the implications of events such as an aging population, extreme weather due to climate change, or infrastructure that is unused due to social and technological changes [63]. In the model, the issues discussed here form the basis for the maximum size of infrastructure, while assessing the future demand for new mobility systems, a shared mobility modes demand that is traditionally ignored. This approach prevents frequent system breakdown such as excessive delays, crash-prone clusters environmental degradation and the funding trap of maintaining oversized "complete street" infrastructure.

3 Formulation of a Mobility Ecosystem in the City Planning Process

With the uncertainty surrounding new mobility systems and their impact on sustainable and shared mobility, the proposed planning model aims to answer two questions which is generally not considered in the traditional mobility planning model: (1) what quantitative process in mobility planning can take into account the optimum size of infrastructure or services while maximizing social, environmental and economic well-being of inhabitants?; and (2) what policies can create a mobility ecosystem that keeps "sustainable mobility as core" service and provides incentives to integrate innovative mobility options through the rethinking of land-use strategies and the reallocation of public space or assets toward space and time efficient modes? To establish a link between two objectives, this section formulates the path to quantification and integration of all ecosystem elements into the city's mobility planning process while identifying public policies to achieve shared goals.

3.1 Process and Resources for Mobility Ecosystem Planning Model

Truly smart mobility planning only emerges if inhabitants participate through a transparent process that includes, for example, networking capabilities that link inhabitants to government policy making, smart open crowdsource data, and an appropriate mobility assessment and implementation process. The resulting smart system offers a sociable and more efficient system without imposing order from city planners or traffic engineers. Figure 4 shows the layers of mobility ecosystem planning model and development process. The model first lays out an overall path of transformation to a future ecosystem that maximizes the social, environmental and economic well-being of users. The development of basic principles including limiting boundaries or constraints and interdependency between six fundamentals elements is performed. The second stage establishes the link between the policy variables of land use and mobility options while formulating the multimodal

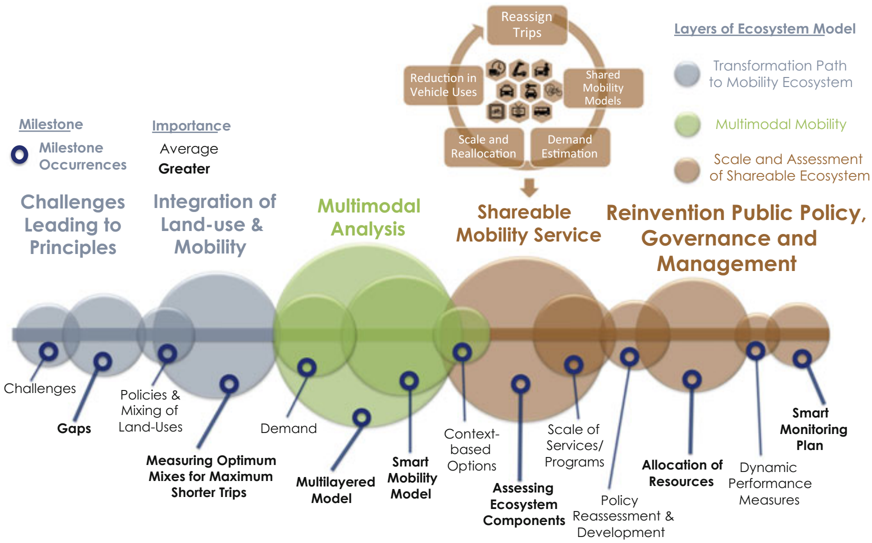

Fig. 4 Development of layered framework of mobility ecosystem planning model

demand forecasting and infrastructure needs assessment process. Finally, the demand and supply scale of shared mobility is developed with innovative policy and implementation strategies that minimize or eliminate negative impacts on quality of life.

3.2 Development of Quantitative Model for Mobility Ecosystem Planning

Transformation Path to Mobility Ecosystem that Maximizes Human Well-being According to the concept of "Systems approach to Sustainable Mobility" [19, 64], exponential expansion of new systems is not sustainable. If sustainability constraints (E) are introduced into system dynamics through economic fundamentals (F) and mobility policies (P), a new innovative mobility ecosystem (IM) would be produced within a practical timeframe (t) while identifying initial conditions of mobility (EM) and satisfying a set of necessary conditions for economic, environmental, and social effects to maximize the well-being of the community. The well-being of the community is summarized in a genuine progress indicator, GPI, which represents the quality of life of city residents. The path to a desired level of mobility ecosystem (MES) is

$$\text{MES}_{t+1} = \text{EM}_t + \Delta\text{IM}_t(F, P)$$
$$\Delta\text{GPI} = \text{MES}_{t+1} \pm \sum E_{i(t+1)} \geq 0$$

Aggregate sustainability constraints will be positive and identified through investigation of the limiting boundaries of each of the six fundamental ecosystem elements (FE) and investigation of the net benefits achieved through the progress of sustainable, shared mobility using policy incentives and strategies.

$E = \int$ (FEi) where i represents number of fundamental ecosystem elements.

Initial Multimodal Model—Bringing diversity in multimodal mobility planning: Smart Growth policies pertaining to built environment variables and mobility accessibility are strongly associated with vehicle use including Vehicle Kilometres Travelled (VKT) and determinants of sustainable mobility (such as Smart Growth Index (SGI) Model [65, 66]). VKT is strongly correlated to measures of accessibility to destinations and street network design variables. The policy variable (P) is a function of six city building fundamentals, denoted here as 6 Ds. The 6Ds are: 'density'—residents plus employees divided by land area; 'diversity'—the jobs–population ratio; 'design'—a combination of sidewalk completeness, route directness, and street network density; 'destination'—regional accessibility; 'distance'—the distance to the nearest transit or ecomobility stations or stops; and 'digital access'—information and telecommunication technologies [3] for sharing/on-demand services).

$P = \int$ (Density, Diversity, Design, Destinations, Distance to Transit, Digital Access).

These key policy variables enable city residents to take shorter trips and minimize the burden on peak hour travel. Shorter and Internal trips (I) are generally less than 5 km, an ideal distance for a combination of walking and cycling or innovative options such as bike share, micro-mobility, or shared mobility options. Maximizing internal trips is a principal indicator of complete communities and a function of diversity of land use, density, and physical and information access to the nearest sustainable mobility services [66].

Internal Trips (I) = $\int$ (Density, Diversity, Mode Share and Access)

The remaining external trips (E), trips that are relatively longer, could be completed by public or shared/on-demand transit, rideshare, carshare, and carpooling options. Every trip from any land use starts as a person trip (T_p) and a combination of internal and external trips of traditional mobility modes (m): vehicle (V), transit (T), bicycle (B), and walk (W) where VO is vehicle occupancy [67]

$$T_p = \text{Internal Trips}\,(I) + \text{External trips}\,(E) = (T_v * \text{VO}) + T_T + T_W + T_B$$

Person trips are usually derived from trip rates (T_m) for each mode with intensity [gross floor area (GFA)] and unit measurements. A is the unit of GFA used for comparing land-use types (l)

$$T_p = T_m * \mathrm{GFA}_l / A$$

Finally, trips for each mode (MT_m) are generally estimated using area modal share (MS) of all types, original sustainable modes (m), and major destinations (dir) within or outside the city

$$\mathrm{MT}_m = T_p * \mathrm{MS}_l^{\mathrm{dir}}$$

Final Mobility Ecosystem Model—Scale and Assessment of New Shareable Ecosystem Elements: However, traditional multimodal models generally ignore the simple reality that travel behavior could have been different if smart technologies, real-time information, and easy access to multiple shared/on-demand mobility options were available to individual users. Adoption rates (AR) for innovative and shared mobility options (n) determine the nature and scale of new demand created by new technologies. Adoption rates are a key factor affecting vehicle–owners and drive alone trips (a_d), and nondrivers or persons without vehicle access (a_0). Nondrivers and persons without vehicle access are particularly important in estimating the use of innovative options available in their area. While total innovative mobility trips (IMT) will increase with increasing values of a_d and a_0, vehicle traffic will reduce under an $a_d >> a_0$ scenario (a positive adoption rate) and increase under $a_d << a_0$ [14]. Hence, innovative mobility trips for different contexts (geographic location, i) and level or technology (t) can be estimated.

$$\mathrm{IMT}_n^i = \mathrm{MT}_m * \mathrm{AR} = \mathrm{MT}_m * (a_d + a_o)_t$$

City building policy incentives with appropriate density, easy access to alternative options for different demographic groups and socioeconomic activities, and connecting technology to transit and other sustainable modes of network (P_{IMT}) increases positive adoption rates.

AR ($a_d >> a_0$) = f (demographic variables, socioeconomic variables, density, level of smart technology available) = f (P_{IMT}).

Supply constraints on innovative and shared mobility services determine the service parameter (SP) of each system. Therefore, the number of adjusted innovative mobility trips for a certain area can be derived.

$$\mathrm{IMT}_n^i\,(\text{adjusted}) = \mathrm{SP}_n * f\,(P_{\mathrm{IMT}})$$

Adjusted total innovative mobility trips produce the ultimate mode share of the final mobility system model.

4 Results and Discussion on Outcome of Mobility Ecosystem Model

This section describes all the elements of the proposed mobility ecosystem model, starting with the basic layers of the model for each fundamental element, followed by a brief analysis of the results and impact on current public policies and strategy aiming to implement a new mobility management process. As described above, interdependent modules for each fundamental element are measured against limiting boundaries or constraints to maintain the sustainable carrying capacity of a city.

4.1 Sociability: Reinventing Multimodal Mobility with Social Innovation

Identifying the social and demographic lifestyle changes and how they will transform the three key mobility planning factors (adoption rates of innovation mobility options, corresponding emerging travel patterns, and configuration and service parameters of the new mobility system [12, 68–70]) is the most difficult part of the proposed model. Public policies and economic fundamentals will determine the scale and levels of these planning variables. Real time and open or crowdsource data, therefore, is a vital part of identifying the trends that turn into mobility needs and developing quantitative process and evaluation models for each mobility option. The proposed model of a future mobility ecosystem must be able to support people and the choices they desire with minimal constraints. In order to achieve this, three levels of adoption rates were assumed: Level 1 is the basic shared systems currently available, Level 2 takes into account available connected and real-time technology, and Level 3 recognizes how people's values are shifting under economic realities and imminent environmental pressures. Among the shared vehicles systems, three levels were assumed: basic sharing technology, connected and electrical products, and fully autonomous technologies.

However, quantifying adoption rates of different emerging modes or services is a perilous task that may lead to overestimation of technology capacity and the timing of full market penetration. To avoid this pitfall, available mobility options and emerging technologies and the response to them were tested iteratively, particularly in a set of pilot project partnerships. These tests identified the challenges and lessons and learning process required to develop fair policies that balance public safety and well-being and create an opportunity for service providers. Through this trial and testing process, a new mobility ecosystem emerges for each planning area (see Fig. 5 for Toronto examples) with an improved understanding of context and local mobility cultures and demographics.

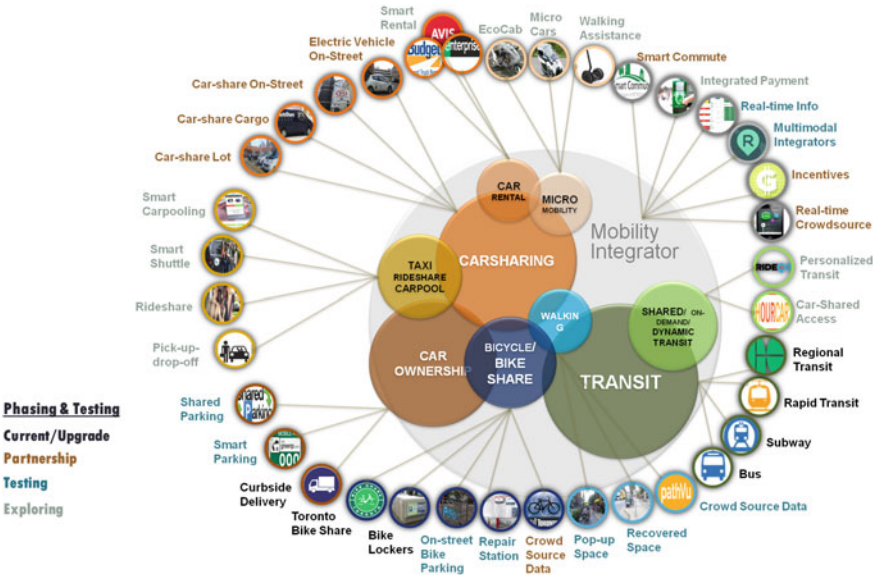

Fig. 5 Emerging social framework and adaptation and testing of mobility ecosystem

4.2 Smart Growth: Integration of Land-use and Mobility

A complete mobility ecosystem depends on diversity of mobility options, and variation in smart land-use policies. To establish the link between smart growth polices and the mobility ecosystem elements described in Sect. 2.3, the model integrates five layers of policy variables (Fig. 6). Firstly, appropriate share and right mix of land-use policies were tested against shared internal trips [30] by several activity centers in the city. Secondly, through iteration and testing [71] in the second stage, internal trips in planning areas were estimated against the optimum share of nonresidential and intensity of diverse land-use. Thirdly, modal shares of all fundamental modes were produced for all land-use and directions of travel within or outside the city. Context-sensitive and reliable targets were adopted using limiting boundaries of density and sustainable mode share (Fig. 4) and a citywide internal trips scale (Figs. 6). Fourth, person trips, multimodal trips, and parking space demand [72] for each mode of mobility were estimated to realize the scale and number connections for each area. Existing multimodal trips, mode share of transit station users, and trips generated by other developments immediately next to planning areas were added to the total future multimodal trips. Finally, multimodal trips were reassigned into the "shareable mobility service" mode to generate the scale of demand for all available or potential future shared mobility systems within the planning areas (Fig. 7). The impact of shared mobility including all demand management measures on parking was reassigned in similar fashion. Depending on

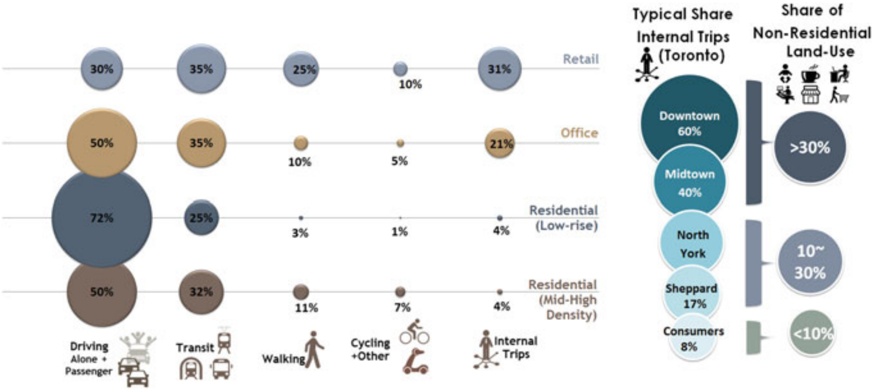

Fig. 6 Diversity of land use and context-sensitive nature of human travel pattern

Fig. 7 Example of multimodal innovation mobility model on land-use intensification

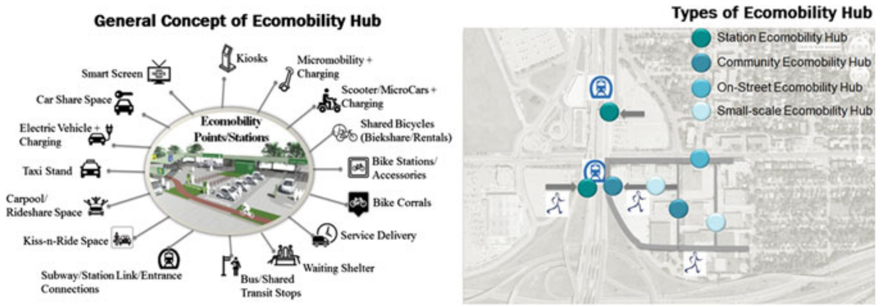

Fig. 8 *Example* of Smart and Easy Access: Ecomobility concept—a multimodal one-stop points (*Centre Image Source* Sophia von Berg, Multi-mobility, Institut für Verkehrsmanagement, 2016)

area context, the model estimates a reduction of 15–26% in the number of vehicle trips and a reduction of 20–40% in parking demand Relevant polices and incentives relevant to area specific zoning by-laws were developed to encourage optimum share and diversity of land-use.

4.3 Smart and Easy Access for All Mobility Users

Quantitative assessment generates the total demand for each mobility modes (both traditional and new) in the ecosystem and the facilities required for each planning area. Acceptable walk sheds to different modes or service station locations is applied to make sure people can access modes easily and walk safely (walk shed varies with mobility options: Bike parking/walkway 100 m, Bus/ped crossing 200 m, Bikeshare 300–400 m, Car-share 530 m, rapid transit 800–900 m). Common measures of multimodal area wide level-of-service [73], the connectivity index (for active modes, the acceptable range of the index is 1.6–1.9) and the pedestrian directness index (the acceptable range is 1.5 or less) are used to ensure that acceptable levels of the physical network infrastructure are in place for accessing mobility service locations. Ecomobility station ideas and short walking distance to neighborhood promenades or hubs where all mobility services are available were developed to ensure integration for easier and smarter access to existing transit or future mode infrastructure. Quality of service in terms of waiting time and service frequency was identified for each service mode to make sure reliability and convenience services are maintained. This enables the development of capacity of all modes or services to match future total mobility demand for planning areas. Finally, connected technologies and real time display or smart screen requirement policies inform area residents or visitors about available service, service status, location or service disruption. Connected technologies also ensure users can pay, book, and locate services. Using nine shared mobility sub-models, the scale of demand, location ecomobility hubs and distribution of shared service were plotted on a base mobility network in order to determine how existing/future public space and connecting private space need to be redesigned and how to reallocate space accordingly (see Fig. 8).

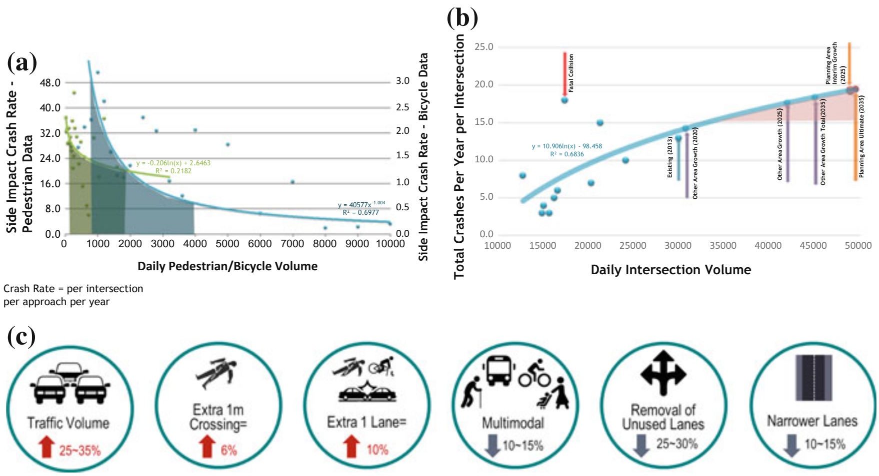

Fig. 9 Summary of sustainable approach to safety in community planning model

4.4 Safety First Approach

Introduction of safety into a proposed mobility ecosystem establishes interconnection between public policy around the safety and overall benefits of sustainable and shared mobility systems. Using local area crash data, initial and effective boundaries (see shaded area in Fig. 9a) of pedestrian and bicycle usage are established where the “safety in numbers” effect becomes strongest, reducing all types of crashes, and where the slope of crash rate decline stabilizes. Since pedestrians, cyclists and vulnerable citizens experience higher crash rates before the initial boundary is reached (roughly 1000 pedestrians and 200 cyclists per intersection in peak hour or 250 pedestrians and 50 cyclists in peak hour of any street segment), it is absolutely critical to implement safe infrastructures and definitive safety policies as fast as possible to shorten the path to achieve initial boundary conditions. The final boundary is drawn where additional land-use intensification encourages more pedestrians and bicycles gradually diminish. A second layer of safety policies is supported by the vehicle traffic reduction strategy, i.e., polices that reduce the number of vehicles in favor of higher transit and shared vehicle usage. Comparing similar proxy sites, an expected crash level is established using a safety performance function approach. However, the expected crash level may be higher in less safe cities (see shaded area in Fig. 9b) and it may be unacceptable to continue the current trend. A community safety planning approach [58] incorporates social and demographic variables and combines crowdsource hazard data and public input and statistical analysis to generate net safety benefits by reducing the number of crashes. The final layer of safety analysis investigates detailed traffic and geometric conditions and identifies major causes of higher crash rates (Fig. 9c). Net safety benefits are estimated to be a 20–40% reduction in the crash rate. These findings indicate right-sizing streets and intersections and reuse unused vehicle spaces are critical to address safety issues in the mobility planning process.

4.5 Recommended World Class Infrastructure

Quantification of the scale of demand and supply of sustainable and shared mobility programs and infrastructure from the model provides an excellent opportunity to redesign and reallocate public spaces to complement the area’s mobility needs. From a political and human psychology perspective, it is difficult task to retrofit existing infrastructure. It is relatively easy for new neighbourhoods if mobility stakeholders understand and are able to visualize their mobility challenges. In order to achieve the objective of quantifying infrastructure needs, the infrastructure of existing streets, public spaces and parking was reviewed (Fig. 10). The results showed that enlarging an intersection by adding lanes reduced capacity by at least 25–30% compared to normal intersections comprising a five-lane cross section.

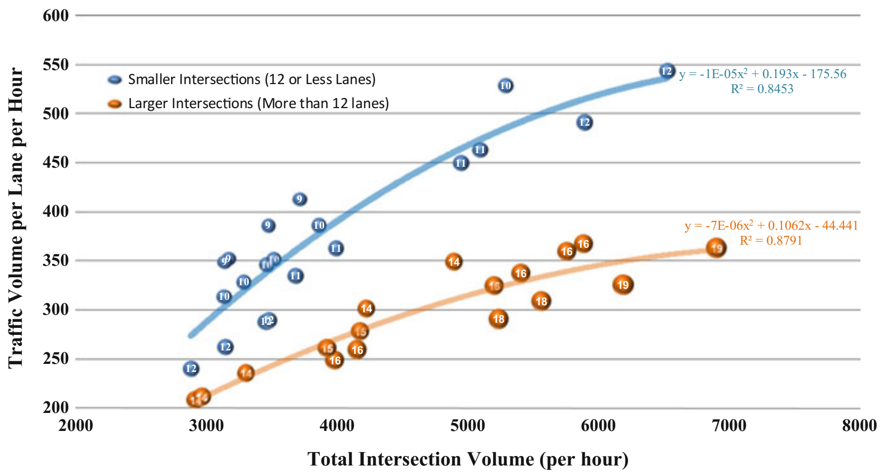

Fig. 10 Limiting boundary of physical capacity expansion of mobility infrastructure

The “wider is safer” approach without any scientific basis resulted in 21–25% of pavement dedicated to vehicles being unused. A capacity review of right-turn lanes also reveals that most of these lanes are not warranted as they are used less than 10% of the time during peak hours (only 3% in 24 h). A review of existing speed reveals that more than half of drivers disregard posted speed limits, with 15% drivers traveling more than 65–70 km/h, roughly the average speed of highways. These results have lead to specific policies that change traffic engineering practice and set limits on unnecessary infrastructure expansion.

Several strong and direct policies can be developed with the help of quantified future shared mobility demand, and a comprehensive review of existing space, street space, and parking area. First, redesign existing curb space or lanes toward shared and sustainable mobility uses. Second, reallocate unused right-turn lanes to create space for short and easy access to shared mobility services. Thirdly, reallocate corner spaces and reduce capacity of local streets to create parking laybys for priority users and shared mobility services. Fourthly, reuse recovered corner space for publicly accessible bikeshare, placemaking, and enhanced streetscape. Fifth, develop partnerships with private property owners to create ecomobility stations and maintain/operate services that provide access to tenants and visitors while sharing unused parking spaces. This is achievable through connected technologies and the release of idle capacity. Finally, multimodal level of service and risk indices were applied to quantify the service improvements by downsizing intersections and streets, and introducing frequent safe crossing locations (Fig. 11). Early results obtained from sites with world class infrastructure indicate that better street design did not slow down regular vehicles, but did slow down speeding vehicles. Livable street designs and reclaimed places invite people to interact with people, express themselves and play—a sign of a healthy and livable city.

Fig. 11 Example of world class infrastructure planning and assessment

4.6 Smart Use of Energy, Environment, and Healthy Planning

The new quantitative science of cities is becoming possible because of the increasing availability of information, particularly the availability of key performance indicators from quantitative mobility ecosystem models. Combining model outcomes, novel measures of human and social activity, and scientific tools or standards developed by leading organizations, the model estimates net environmental footprint reduction [74], energy consumed by passenger vehicles [75], reduction of private vehicles uses per household [29], and the health impact [27] and economic benefits of pedestrian and cycling policies and infrastructure [28]. Compared to low-density land use, the proposed mobility ecosystem for suburban centers along with the mixing of land-use is expected to reduce energy resources and pollution from vehicles by roughly half (Fig. 12). Urban growth centers or downtown areas combined with sustainable and shared modes could reduce up to 55% of energy, vehicle usage and the carbon footprint. An additional 15 and 5% of health benefits can be achieved through policies encouraging sustainable and

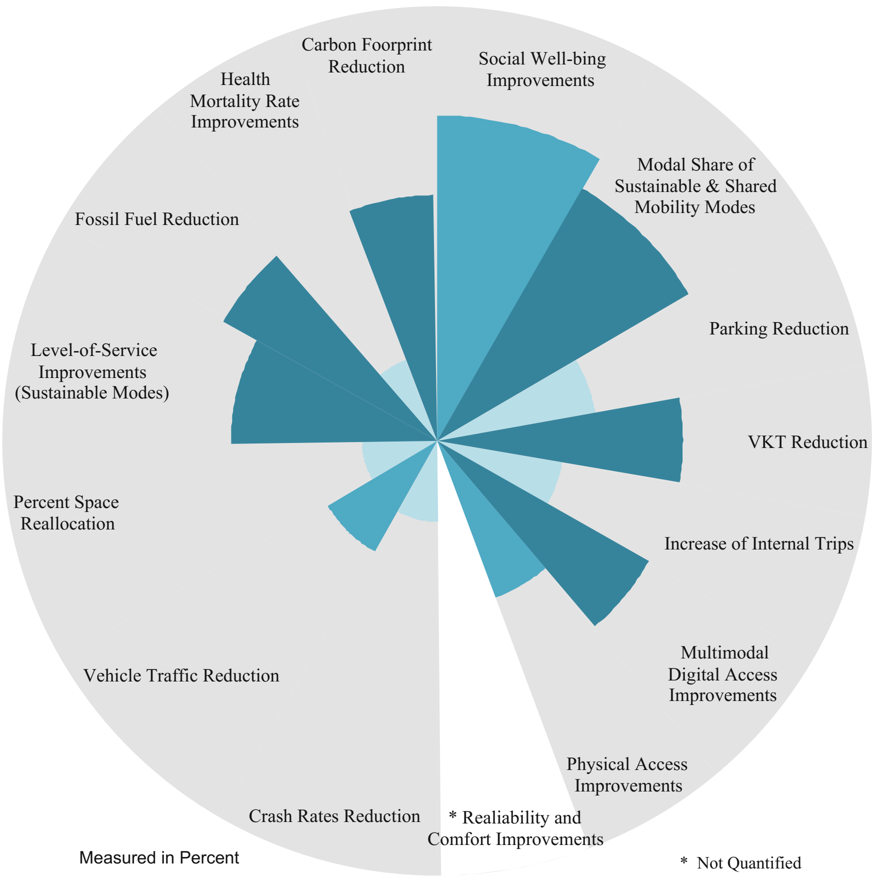

Fig. 12 Estimation of social, economic and environmental improvements within the city's carrying capacity and boundaries

walking and cycling infrastructure, respectively. Figure 12 summarizes the aggregate sustainability benefits of the complete urban mobility planning ecosystem.

5 Moving Forward: Implementation Process and Partners

The complex structure of the mobility ecosystem requires a departure from traditional isolated governance and the resulting fragmentation of the mobility delivery system. Private stakeholders, community partners and third-party service providers will all play a critical role in implementing this new model of mobility planning in conjunction with public sector.

5.1 Incremental Steps and Evolution of Mobility Ecosystem Planning

Key to the successful implementation of the proposed mobility ecosystem are a set of initial prototype pilot projects, the evolution of the initial model, and the lessons learned from successful projects. Demand for connected multimodal services has created several successful business models around the world. Several German cities have installed one-stop mobility service points with a surprisingly high adoption rate and popularity among the residents [76]. Austrian mobility points provide direct service to housing estates and neighborhoods [77]. The Toronto Parking Authority has started to integrate several mobility services, and is working on bike-share expansion and an on-street app booking system. The mobility services include car-share, electric vehicles, bicycle parking, and smart parking payment. A small scale application of an innovative mobility neighborhood based on this new mobility model is currently underway in the Toronto's Tippett-Wilson regeneration area. This project includes a complete redesign of street curb space, multiple mobility connections, and smart screen and digital information points at building entrances. On a larger scale, the old model of travel demand management approach and delivery systems are currently undergoing major changes to embrace an "Ecomobility Hub," a multimodal service point, at Toronto's Consumers business park. This project is a direct outcome of the new mobility planning approach introduced in the Tippett area. However, the barriers and challenges are endless. The lack of mobility integrators in Toronto, such as the Finnish monthly mobility package (MaaS model), is holding back the implementation process. A multimodal service by OEMs similar to Toyota's Harmonious Mobility or Ford's shared-transit-based system is currently being tested. An integrated payment system, such as the system available from Moveel or other technology companies, will fill the large void in the current fragmented user interface. The introduction and adaptation of these new applications through appropriate regulations, policies and hard and/or soft infrastructure in the proposed ecosystem will likely eliminate current mobility gaps.

5.2 Critical Changes and Stakeholder Function

The following major changes will be dominant forces in the new mobility ecosystem where different stakeholders play different roles, multidisciplinary public–private innovation become common practice, and private and public leaders develop a shared vision:

- **Mobility-as-a-service package**: The private sector may take the lead in bringing innovative products to general users while the public sector cooperates to facilitate the creation of a platform that regulates and promotes multimodal options, allowing these options to thrive.

- **OEMs multimodal business**: Similar to the model envisioned in SMART [19], automotive manufacturers and technology companies develop end-to-end mobility products and deliver services through the public sector with proper regulation and security/safety assurance.
- **Ecomobility points**: Public parking authorities and multimodal business providers cooperate with private developments to install a network of ecomobility points or stations that provide one-stop service points that create seamless link between all modes.
- **Public policy development**: The public sector revamps official plans to recognize new private sector mobility products/services and their new hard and soft infrastructure requirements. The public sector also reduces or eliminates unnecessary infrastructure or services that promote unsustainable use of vehicles.
- **Redesign of streets and curb side management**: The public sector initiates the process of street space allocation while local business improvement or community organizations maintain certain portion of streets or facilities along building frontages.
- **Redesign of building frontage**: The real estate and commercial sectors redesign building access points to follow public accessibility policies promoted and regulated by the public sector.
- **Digital access points**: Supported by the public sector's demand management policies, private sector communications companies develop and install innovative and integrated realtime information systems with smart screen display.
- **Rethinking public space**: The public sector works with the retail and commercial sectors to create or reallocate public spaces as part of the move toward a new and shared commercial/public economic model.
- **Shared and smart parking**: The public sector creates demand based parking policies. The real estate and development sectors partner with smart technology companies to introduce the infrastructure required for the demand based parking policies.

6 Summary and Conclusions: Vision for People-Oriented Mobility Ecosystem

Today, the dynamics of mobility technologies and options include environmental and health issues, and the need to establish a sustainable society. In reality, easy access, safer, reliable and comfortable multimodal systems change daily travel patterns, particularly work trips. If shared mobility is gradually implemented through future growth, connected mobility systems will significantly alter travel patterns. Since these mobility services are shared, coordinated area approaches are critical to securing and implementing sustainable and shared mobility services.

Given that transit infrastructure is the backbone of the Canadian mobility landscape, the study recommends the following process for the adaptation of innovative options and the integration and transformation of traditional sustainable modes: (1) if done properly, while increasing society and natural well-being, innovation and shared/on-demand technologies have a greater impact on parking supply and reduction of single occupant vehicle uses, and thus, reduce crashes, environmental pollution and low-carbon footprint; (2) instead of an adversarial reaction to new systems, test new options and technologies, and integrate into mobility planning processes once a system becomes a mature and viable; (3) integrate existing and emerging mobility and smart growth options in planning processes through collaboration between different levels of public agencies, mobility integrators and knowledge institutions; (4) using a quantitative planning model, estimate the scale and impact of innovative mobility options and evaluate and monitor progress using smart and crowdsourcing data; (5) create implementation tools and policies from scientific evidence through best practices of technological adaptation, and encourage policies and incentives to reduce inefficient use of vehicles and discourage negative impacts of technology that may become a threat to sustainable mobility modes; and (6) develop public policies that change the process of infrastructure planning, and make it easier to redesign public spaces, repurpose lands, and create ecomobility hubs and community interaction places through connected technologies and real time access to mobility service locations or programs.

Echoing an ancient Peruvian proverb, the marriage between technology and future mobility planning without improving social well-being will be worthless. Believing that mobility planning practitioners should support a more efficient and modern scientific innovations mobility system, the study recommends natural adaptation of the emerging mobility paradigm through the reinvention of people-oriented public policies—with shared incentives and goals between collaborative governance structures and mobility integrators—that improve quality of life of residents and improve genuine progress indicators. A steady and organic adaptation process of innovative technologies will enable cities to replicate nature's model of intricacy and sophistication into a new mobility ecosystem that rebuilds human social capital through peer trust.

Disclaimer The views expressed in this article are those of the author and do not necessarily reflect the views of the City of Toronto or other cities where the "Mobility Ecosystem" framework was applied.

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