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Iterative urban design and transport simulation using Sketch MATSim

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ABSTRACT

New transport technologies have historically influenced how cities are shaped, while urban form is known to influence travel behaviour. But this reciprocal relationship is seldom operationalized in practice due to the disciplinary gap between urban design and transport planning. The two are often linked through a 'predict and provide' workflow, which is problematic in the context of emerging technologies such as AVs. This paper argues for a more iterative design and transport simulation workflow, through design experiments. One design experiment is illustrated using Sketch MATSim, to investigate the impact of network design on the performance of shared automated vehicles.

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Introduction

There is a strong reciprocal relationship between built form and transport flows (Bertolini 2017; Boarnet and Crane 2001). However, these two aspects of cities are studied under distinct disciplinary traditions, with very little interaction between them. Built form has been the mainstay of urban design and planning while transportation flows that of transport planning and traffic engineering. The two are typically linked through a '*predict and provide*' process (Hutton 2013). Traffic flows are predicted in transport planning through quantitative models, and these predictions are used as a starting point in urban design to provide infrastructure using normative design principles. The transport models that are used to predict flows tend to take a very coarse view of the urban form, aggregated to traffic zones or census tracts, limiting ways to explore the relationship between urban form and travel behaviour (Handy 1996). Urban design methods on the other hand tend to be more spatial and under-represent the temporal nature of transport flows (Batty and Marshall 2012). Latest technological developments in transportation pose new challenges for urban design and transport planning, which are incompatible with the traditional *predict and provide* approach.

The urban transportation sector has witnessed several technological innovations in the last two decades, with an accelerated pace of development in vehicle automation technologies

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(The Aspen Institute 2017a), widespread implementation of platform-based ride-hailing systems in most major metropolitan regions around the world (Clewlow and Mishra 2017), and growing connectivity and sensing in our environment, marked by latest developments in 5 G technology (Ge, Li, and Li 2017). These technologies have the potential to converge and fundamentally shift existing mobility patterns (Urry 2004), ultimately leading to a larger *'technological shift in transportation*' (Maheshwari 2020). The methodological relationship between urban design and transport planning must evolve to effectively respond to the technological shift in transportation.

This paper argues for a more iterative relationship between urban design and transport modelling, in contrast to the predict and provide approach. An alternative approach using iterative design experiments is proposed, which are simulated in Sketch MATSim. This workflow is demonstrated through one design experiment as a case study.

From 'predict and provide' to an iterative approach

The *predict and provide* approach became popular in the sixties and seventies when planning for transportation was mostly driven by transportation engineers following a distinctly mechanistic approach. The idea that transport planners should not directly manipulate urban form was embedded in this approach (Boarnet and Crane 2001), prompting some scholars to call this process 'predict and accommodate' instead (Rodrigue, Comtois, and Slack 2013). Isserman (1985) in his seminal essay 'Dare to Plan', bemoaned planners' over-reliance on mechanical forecasts and the diminishing role of planners in shaping urban development, leading to new concepts such as 'predict and prevent' (Owens 1995) and 'decide and provide' (Lyons and Davidson 2016).

Over the last decades, transport modelling techniques have become increasingly disaggregated and bottom-up, with advancements in discrete-choice modelling (Ben-Akiva, Lerman, and Lerman 1985) and agent-based simulations (Zhang and Levinson 2004). However, the relationship of these models to urban design is still predominantly defined by the *predict and provide* process (Goulden, Ryley, and Dingwall 2014; Næss et al. 2014), which is especially problematic in the context of the complex web of interdependencies and uncertainties arising from the technological shift in transportation (Gruel and Stanford 2016; Maheshwari and Axhausen 2021; Meyboom 2019; Milakis et al. 2017).

On the one hand, despite computational advances, predictions are bound to be inaccurate as the level of uncertainty increases (Bertolini, Clercq, and Straatemeier 2008; Pearman 1988; Ratcliffe and Krawczyk 2011; Batty 2018). Predictions also tend to have an inherent quantitative bias, focussing on measurable economic, demographic or environmental variables and underplaying social, cultural and political variables. They focus on what *will* be rather than what *could* be (Cole 2001; Shiftan, Kaplan, and Hakkert 2003).

Design, on the other hand, is well equipped to address questions regarding 'what could be', through synthesis (Kolko 2010) and visioning (Shipley and Newkirk 1998), but is often biased towards a spatial view (Carmona 2020), neglecting temporal aspects of transport flows (Cidell and Prytherch 2015; Sevtsuk 2014). Designers also commonly evaluate solutions intuitively and normatively, which can be misleading in the context of the growing complexity and uncertainty of the technological shift in transportation (Cannon 1973; Clarke 2014; Karimi 2012). This points towards a need for a more iterative process that straddles the space between intuitive design and quantitative analysis by enabling a feedback cycle between the two.

The need for such a feedback cycle has long been acknowledged in concepts such as integrated transport and land use planning (Hull 2005; Wegener and Fuerst 1999) and transit-oriented development (Liu, Zhang, and Xu 2020; Motieyan and Mesgari 2018). However, operationalizing this cycle has been a challenging undertaking so far, essentially due to what Hillier (1996) calls, a 'disciplinary apartheid', that exists between urban design and transport planning. Those who analyse urban function cannot conceptualize design, while those who conceptualize design, only intuit function. For example, the three physical roles of the urban street – as circulation route, as a public space and a frontage for buildings – are separately tackled by transportation engineers, urban planners and architects/urban designers, respectively (Marshall 2005). There is also a scale gap between these disciplines, where transport planning begins with the regional scale and loses relevance at the local scale of decision-making. In contrast, urban design begins with a group of buildings but hesitates to operate at the city level (Hillier 1996).

To overcome this disciplinary apartheid and operationalize an iterative cycle, analysis methods in urban design and transport planning need to be reconciled, beginning with and how the reality is 'modelled' in both disciplines.

Modelling for an iterative workflow

Both transport planners and urban designers heavily rely on modelling as a method of analysis and sense-making, respectively, but the models they use for analysis are fundamentally different by nature. This has been a serious roadblock in establishing a two-way dialogue between the two disciplines.

A model is nothing but simplified representation of some real-world condition, constructed to test policies for new technologies and behaviours that do not exist in the real world (Allen 2012; Ligtenberg et al. 2004). Transport models are analytical, which replicate the system of interest and its behaviour through mathematical equations based on certain theoretical statements about it (Ortúzar and Willumsen 2011). These base assumptions are used to derive predictions for future transport flows, typically using a four-step model (McNally 2007) at a very aggregated scale.

Urban design models are descriptive rather than predictive, represented as a physical scale model, or CAD and GIS models. Once the traffic flow predictions are estimated, the dialogue with design rarely goes beyond negotiations on space allocations for transport modes. For example, feeding back change in traffic flow predictions in the transport model based on a walkable design that nudges people towards using public transit is rarely seen. This is mainly due to the aggregate nature of transport models. Disaggregated discrete choice models in transport attempt to address this issue to some extent by refining predictions at the individual level, but their spatial resolution remains highly aggregated. Disaggregate models do not consider mutual dependence between trips, people and activities (Iacono, Levinson, and El-Geneidy 2008; Wise, Crooks, and Batty 2017) and ignore diversity among individuals and urban form aspects (Zhang and Levinson 2004).

These issues are compounded by the technological shift in transport, where the added complexity gives rise to unexpected emergent phenomena over time. Urban design models tend to be static, showing one slice of time, and fail to capture emergence. On the other hand, recent advances in agent-based modelling in transportation can reveal patterns of change over a period of time. In fact, agent-based models are the most appropriate method of transport analysis in the context of the technological shift in transportation, since they best represent the dynamics of a complex system and emergent effects of new transport systems such as mobility on demand (Navidi 2019; Ciari, Balmer, and Axhausen 2009). But these models have often been criticized for being overly complex, data-hungry, costly, and excessively large in scope, with too coarse a level of detail for actual policymaking (Batty 2008; Bertolini 2017; Myers 2001; Owens 1995; Pearman 1988; Lee 1973). Since design processes tend to be highly iterative, involving multiple options and scenarios, large complex models are hard to integrate in the design process. Therefore, a 'design experiment' method is proposed, that simplifies the models in both design and transport planning to support a feedback loop between them.

Design experiments

There is a common belief that the more detail a model contains, the more accurate it will be, leading to increasingly complex and expensive models. However, the key to enabling an iterative cycle between urban design and transport planning is to move away from highly detailed consolidative models, towards exploratory models, i.e., 'providing partial (or incomplete) information to the model in order to pursue partial answers' (Bankes 1993). In this conceptualization, a model is a 'heuristic planning tool' (Portugali 2012); a 'narrative' or 'storytelling tool' (Guhathakurta 2002); a 'pedagogical tool' (Batty 2008) in how it informs and extends our understanding; or a 'mediating tool' (Perez, Banos, and Pettit 2017) accompanying knowledge building and sharing. Exploratory models represent a selective reality relevant to the research question, and can only indicate the probabilities of the city evolving in a specific direction, given a set of artificial conditions.

One critique of this approach is that when we reduce the level of detail and oversimplify a model, it also becomes increasingly inaccurate. However, a set of many inaccurate models can still be 'useful' to obtain structural results on the comparative performance and trade-offs involved. As long as the ensemble is sufficiently diverse given available knowledge, computational experiments can be performed to infer the properties of the system. Such an ensemble of models driven by a specific question of interest is termed as a *Design Experiment* in this paper.

For example, consider a hypothetical study on the relationship between network connectivity, land use mix, and public transport provision. Each variable can have a plausible range of values from low to high, resulting in a virtual ensemble of models within a vast 'attribute space', corresponding to the highlighted cube in the leftmost diagram in Figure 1. Every point within this attribute space is a plausible model. As the number of variables increases, the number of possible models increases geometrically. Since it is not possible to run all models, a set of 'useful' models must be selected from this near-infinite ensemble for a design experiment.

To guide the search for 'useful' models, heuristics are used. This is an interactive process that involves decision-makers and stakeholders participating in model selection, construction and simulation. In the given example the three values of interest can be identified for networks and land use and two for public transport . Based on these values, a reduced attribute space is produced, as shown in the

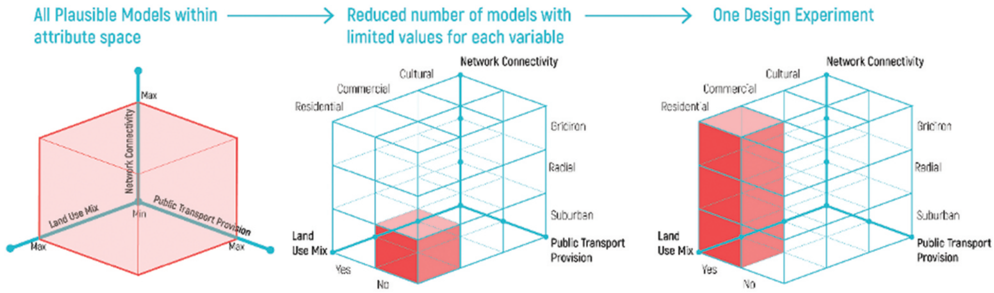

Figure 1. Reducing from all plausible models within attribute space to limited number of models with limited values for each variable, to finally develop one design experiment.

diagram in the centre of Figure 1, with 18 unique models. For instance, the highlighted cube in the centre diagram represents a suburban residential area with no public transport.

Once the limited ensemble of models is identified, simulating this ensemble quickly and intelligibly remains a challenge. One reason is the lack of appropriate software tools that can run quick transport simulation analysis for planners and designers with limited computational expertise. Current paid software solutions for agent-based transport modelling such as Aimsun and PTV Vissim, or open-source software such as MATSim and SUMO (Lovelace 2021), continue to be complex, data heavy and/or computationally expensive. They are more suitable for simulating final design proposal, but not to test multiple design options at early stages.

There are three essential conditions for software tools required to evaluate design experiments:

(1) *Agility*

The need for quick testing of many scenarios repeatedly puts an upper limit on the time required to run the model (Batty 2013; Grignard et al. 2018). Both Bankes (1993) and Marshall and Gong (2009) *suggest reducing the model to the smallest resolution possible, to make them more agile, understandable and manageable.*

(2) *Modularity*

It should be possible to change the resolution of the model in response to different questions asked during the analysis, thus displaying modularity and ease of reconfiguration (Batty 2013).

(3) *Intelligibility*

To make sound decisions based on model results, the cause and effect relationships should be clear (Batty 2013; Cannon 1973). *The model should be intelligible, such that whatever the output, it is traceable to changes in input values.*

There are several transport simulation platforms which incorporate one or more of these properties to varying degrees, but all three conditions are rarely satisfied. Sketch MATSim, has been developed as a heuristic modelling tool, based on the open-source MATSim framework, to facilitate quick iterative design experiment cycles through an easy-to-use visual interface. It uses low-detail models and a data-driven trip generation framework, resulting in shorter model construction and runtimes. This enables temporal analysis of transport flows for several design options in early stages.

Sketch MATSim and design experiments

Sketch MATSim is based on MATSim (Multi-Agent Transport Simulation) which brings together expertise in traffic flow, large-scale computation, choice modelling and Complex Adaptive Systems (Horni, Nagel, and Axhausen 2016). Simulations in MATSim are based on a co-evolutionary principle, where different species co-evolve subject to interaction (e.g., competition). The process begins with an initial demand, as shown in Figure 2, arising from the study area's population and activity locations. The modelled persons, or *agents*, have a fixed day plan consisting of *activity chains*. After each iteration of the simulation, the agents are rewarded for performing activities and penalized for travelling and arriving late, and assigned a *score* (which is nothing but the utility of the plan), and the agents modify their plan (*replanning*) to achieve the best score, through feedback and mutations, in a co-evolutionary process. This framework encapsulates the three essential properties necessary for modelling design experiments.

(1) MATSim and 'Intelligibility'

Every action in the simulation generates an *event*, an atomic unit of information, which is recorded for analysis. These event records can be aggregated to evaluate the simulation at the desired resolution allowing analysis of cause-and-effect mechanisms across varying levels of detail. However, as the information in the model grows, it gets harder to relate an effect to a specific causal mechanism. Additionally, in its present state, significant technical expertise is needed to decipher the model dynamics and analyse the results in MATSim, to make them intelligible for a non-technical audience.

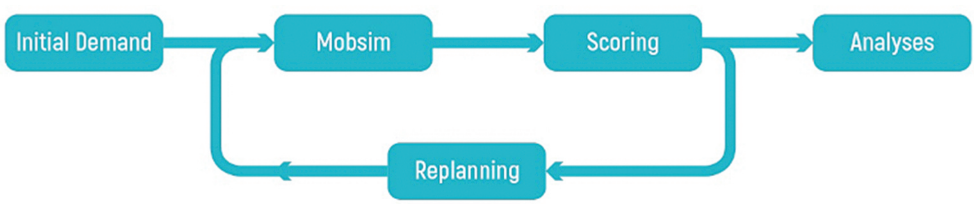

Figure 2. The MATSim Loop.

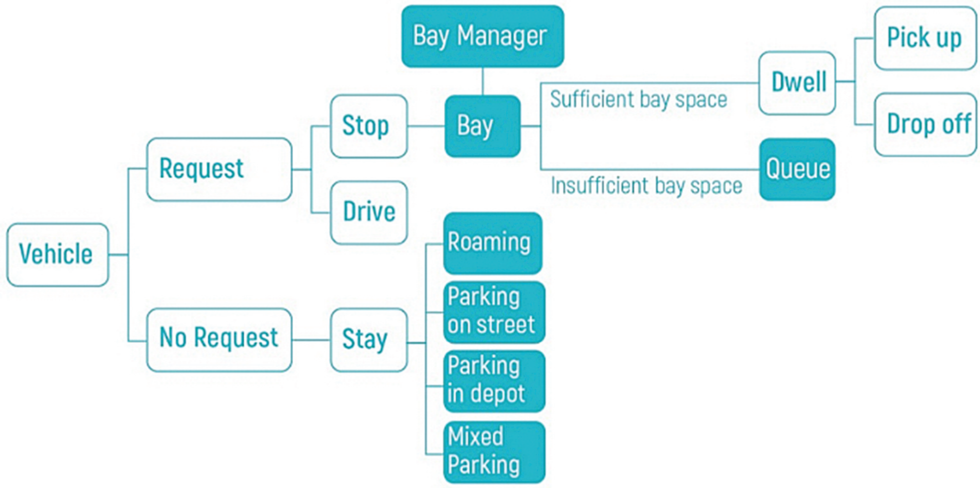

Figure 3. Implementation of spatial DRT.

(2) 'Modularity' in MATSim

MATSim is highly customisable and in recent years, several new modules have been developed in response to the technological shift in transportation. The specific MATSim extensions that are relevant in the context of the technological shift in transportation are: the DVRP (dynamic vehicle routing problem) extension (Maciejewski 2016), which contains a framework for scheduling vehicles according to tasks; the DRT extension (Bischoff, Soeffker, and Maciejewski 2016). The Spatial DRT implementation shown in Figure 3, which includes finer-grained spatial elements like parking and pickup drop-off (PUDO) points was developed for the case study outlined in this paper.

(3) Sketch MATSim for 'Agility'

Commonly, an entire urban system (for example, the whole city) is modelled and simulated in MATSim. But in the context of urban design research, the area of interest is usually limited to the neighbourhood scale. Sketch MATSim maintains the site information at high resolution, while abstracting out the global condition. A fixed number of incoming and outgoing daily trips are assumed for the neighbourhood. Design layers are imported in Sketch MATSim as shapefiles through a user interface, as shown in Figure 4.

The agent's need to travel between activity locations is informed by activity and trip-making patterns observed in areas with similar activity/land-use opportunities using a machine-learning algorithm. Inbound and outbound traffic by various modes can either be generated using the same algorithm or explicitly defined as an hourly schedule of trips entering and leaving the area. This is combined with design inputs, such as network design and land use planning, and processed inputs such as improvements in walkability. The model simplifications, reduction in scale and data-driven demand generation process considerably

Figure 4. User interface for Sketch MATSim.

reduce simulation run times (about 7 minutes per iteration on an average in the case study for this paper).

Sketch MATSim trades-off accuracy with runtime allowing the user to test several design options rapidly. Global events impact local processes and vice versa, but this information is entirely disregarded in the model since all incoming and outgoing trips are aggregated. These design experiments are only useful for exposing structural variations across the model ensembles and to intuit the underlying cause and effect mechanisms.

Case study: network design experiment using Sketch MATSim

The following section illustrates the concept of iterative urban design and transport simulation through a design experiment that investigates how the design of the street network can influence the impacts of the technological shift in transportation, enabled by shared, connected and automated mobility. In other words, how can the street network be designed in order to maximize the benefits of these technologies and minimize their dangers.

Step 1: scanning the parameter space and setting design goals

The first step in defining the experiments is to identify the parameters of interest from all the design solutions that could plausibly be entertained given a combination of factors, including but not limited to, the aspirations of the stakeholders, the available data and the physical properties of the site and the urban context. In this case study, the stakeholder group is defined by the collaborators on a three-year research project funded by the Ministry of National Development in Singapore, to understand the impacts of automated vehicles on urban planning and transport supply. This project allowed close collaboration with multi-disciplinary experts from academic institutes and policymakers in Singapore, allowing a rich and regular exchange with the stakeholder group.

Two targeted design workshops were conducted to reduce the large parameter space iteratively from the initial 15 possible scenario dimensions, as shown in Figure 5, (which alone would result in a combinatorial explosion of 15 million plausible models). The first workshop had 35 participants, comprised of planners, urban designers and transport engineers from government agencies in Singapore responsible for housing, transportation and master planning. The participants were split into four groups and a world café style discussion format was adopted. The groups focussed on identifying the preferred operational model for automated and shared vehicles in Singapore using an exploratory matrix of extreme scenarios. The process involves developing a narrative for each

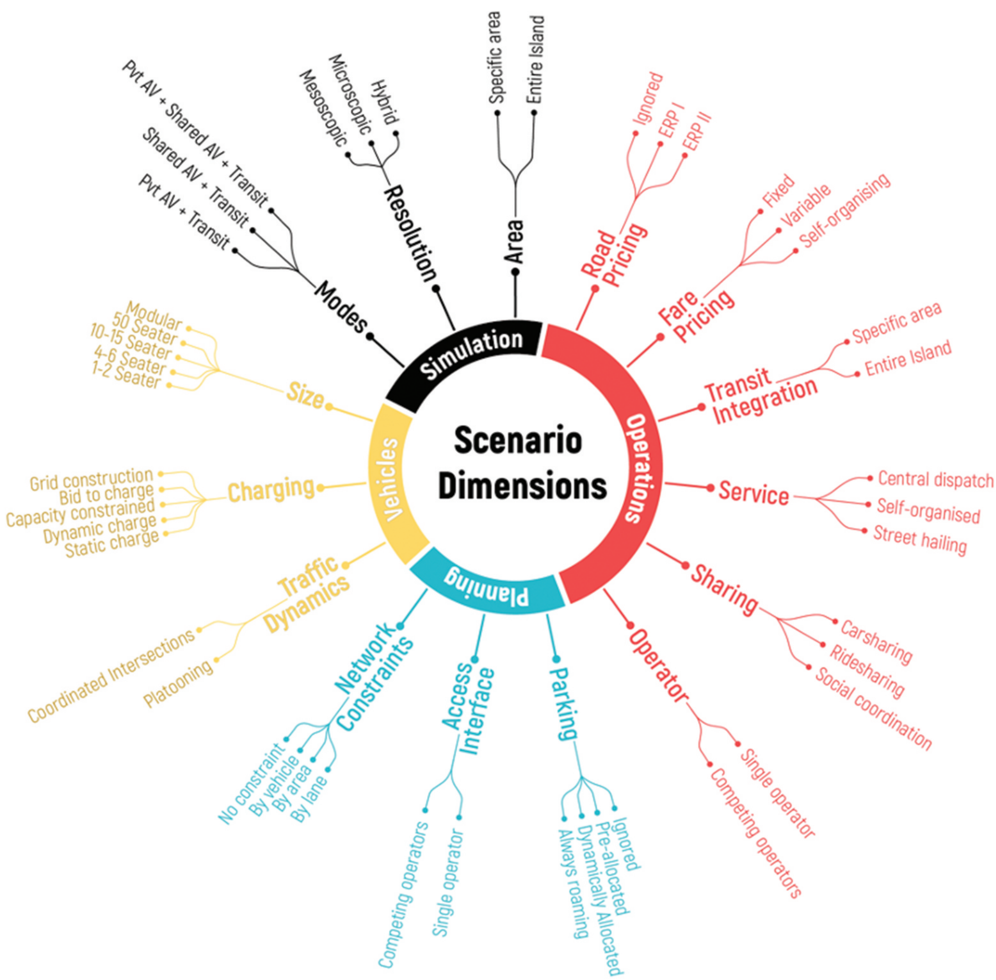

Figure 5. Possible parameters that could be tested.

quadrant of the matrix, representing a different extreme future (Banister and Hickman 2013). A general consensus was reached on the design goal to promote a 'car-lite' future city (Centre for Liveable Cities 2016) as opposed to an 'AV-ready city' (van Arem et al. 2019), where the technological shift would support existing public transport system and not compete with it.

Singapore's residential New Towns were selected as the test bed for the design experiments, to test how different design strategies would impact the transport goals. 'New Towns' are government owned, managed and developed housing estates where 80% of Singaporeans reside. Singapore's reputation as one of the world's 'most active laboratories for experimentation with automated vehicles' (The Aspen Institute 2017b), and that of New Towns as an 'experiment in an urban laboratory' (Liu, Lau, and Loh 1983), make New Towns ideally suited to conduct the design experiments.

Step 2: identifying the questions of interest

The second workshop conducted with the same participants focussed on defining the 'questions of interest', that drive the design experiments. While the points of consensus in the previous workshop helped identify the design goals and intent, the points of contention in turn lead to the questions of interest from the point of view of design and planning. These included design of drop-off facilities, parking facilities, intersections, and network design. Participants were provided templates of design options which they overlaid based on their design goals. Each option was accompanied by a set of pros and cons that were collectively debated. The focus of this case study is the question of network design: How do we design street network for new transportation systems?

Step 3: constructing partial model with 'parameters of interest'

First a 'partial' base model of the Singapore New Town is constructed in such a way that it mimics a New Town in only its essential properties that are relevant to the design experiment – urban structure, density, land use, transportation system, parking and Pick-up Drop-off (PUDO) infrastructure. The seven spatial layers representing the physical environment were constructed parametrically, as shown in Figure 6. This allows quick modification of layer attributes for testing several design options, and can directly be imported in Sketch MATSim as shapefiles for analysis. The initial travel demand was generated external of Sketch MATSim, from the spatial information provided by the layers of the base model. The travel demand generated outside of the site is abstracted into a fixed number of incoming and outgoing trips at two portals at either end of the site.

Once the environment and initial demand are generated, the model is populated with the vehicle stock and service schedule of all available transport options in the simulations. To simplify the experiments, six modes of transport were provided: private cars, automated taxis, automated demand responsive transit or DRT (capacity of 20 persons and 12 persons), scheduled bus service, three mass rapid transit stations, and a pedestrian network. The combination of the seven spatial layers, the resultant travel demand and the vehicle stock with service schedule for public transport, forms the base model.

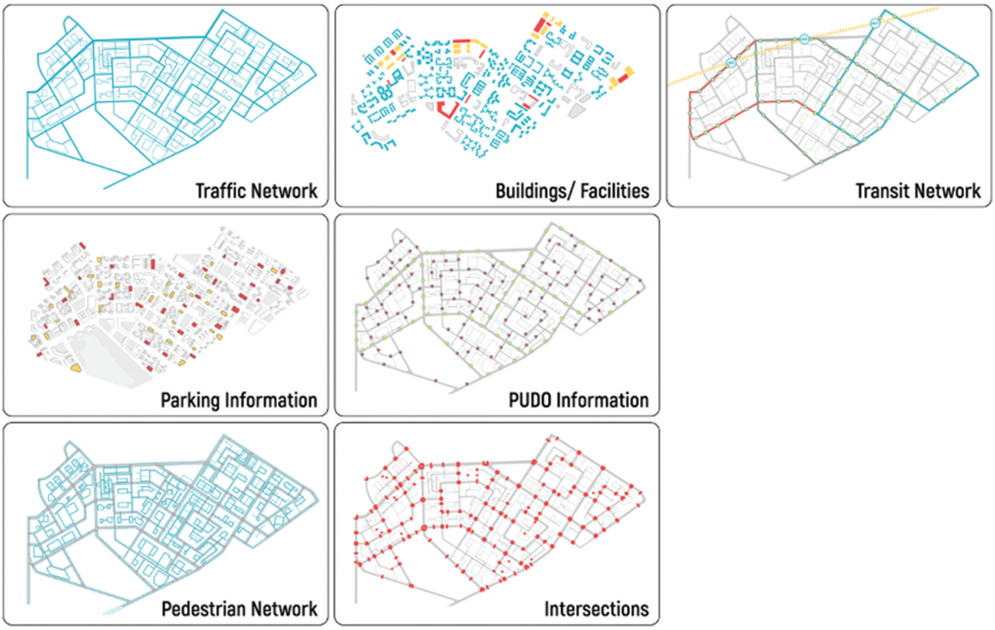

Figure 6. The seven layers of the parametric base model.

Step 4: defining the experiment

This experiment investigates how different network types impact transport flows, when shared and connected automated vehicles are deployed, while all other base conditions remain the same. Three extreme options are created for the network layer: Loops, Grid and Superblock, as shown in Figures 7–9, respectively, while retaining all other layers to default values in the base model. The three extreme conditions are simulated and compared to draw useful conclusions on ensuing trade-offs and cause-and-effect dynamics.

The Loop type refers to a less connected network, with several T-junctions and dead ends, and is more commonly seen in Singapore New Towns, since it discourages through traffic and reduces disturbance in residential neighbourhoods. A common critique of this network type is the low connectivity. All traffic is funnelled through the peripheral arterial roads which can act as a barrier between different neighbourhoods. Vehicular traffic is also forced to make many detours, which might increase Vehicle Kilometres Travelled (VKT), which is used as a proxy here for vehicular emissions.

Grid refers to a well-connected network, with mostly X-junctions, and a smaller distance between junctions, as shown in Figure 8. Grids are among the most typical forms of spatial organization used for planned urban expansion and can be considered the diametric opposite of Loops. The distance between two major intersections is between 300 and 400 metres in Loops, while in Grid the block size is between 100 and 150 metres. Fine-grained grid with small block sizes is favoured by planners based on their apparent benefits for walkability (Jacobs 1961; Boarnet and Crane 2001). Ride pooling may also be more efficient in a grid network due to fewer detours. However, a higher number of intersections could present more points of conflict for pedestrians/cyclists. Increase in through traffic through quieter residential areas could also create some disturbance for residents.

Figure 7. Network design of the 'Loops' model.

Figure 8. Network design of the 'Grid' model.

The Superblock model is a variation of the Grid model with changes in maximum allowable speed as shown in Figure 9. The streets on the edges of the neighbourhood have a high-speed limit, while the internal roads have maximum allowable speed

Figure 9. Network design of the 'Superblock' model.

comparable to that of pedestrians and cyclists (10 km/hr). 100% speed compliance can be assumed here since connected vehicles can be governed through geofencing. While low-speed roads may improve walkability, allowing pedestrians to make more shortcuts, congestion could also increase in high-speed arterials.

It is important to note that the three design options in an experiment must not be seen as an implementable strategy. A network can never be solely classified as a Grid 'type' but is usually a hybrid. However, a homogenous condition is constructed to compare three extremes. Thus, these models are not defined as 'proposals' or 'scenarios', but rather as experiments.

Based on an intuitive urban design principles, some conjectures can be made on how each network type will perform under the given conditions on common performance metrics. These conjectures are summarized in Table 1. Simulations in Sketch MATSim will now be used to confirm (or refute) these conjectures.

Step 5: analysing results – which network performs best?

On most metrics, Superblocks perform better than the Loops and Grids. Based on the results from the simulation, the three network types have been scored on a scale of one to three, three being the best performance and one being the worst, as shown in Figure 10. Three primary conclusions can be drawn from this experiment. First, the disconnected Loop network, which is prevalent in most New Towns in Singapore, currently suffers from the lack of efficient first/last mile solutions, which remains a problem despite the implementation of demand responsive transit. Second, a more connected network topology does not necessarily mean more vehicle sharing, and

Table 1. Conjectures on the performance of the three network types in the experiment.

	Loops	Grid	Superblock
Traffic Flow	No through traffic and more detours may create more congestion	Traffic flow may be better due to the availability of more route options.	Traffic mobility may be smooth on the arterial spine, but low on shared streets.
Active Mobility	Pedestrians may have to take long detours if pedestrian network follows traffic network	More connected network for pedestrians if the intersections are designed with pedestrian priority.	Pedestrian-friendly environment inside the block, but connections between blocks may be difficult.
Transit Access	Longer detours may lead to longer headways between transit vehicles. Walking time to transport hubs might be longer too.	Grid may improve access to transit due to fewer detours for shared vehicles and less walking time to transit hubs.	Depends on the location of mobility hubs and land use distribution inside the block.
Traffic Emissions	Potentially higher overall VKT due to longer detours	More route options, shorter detours will lead to fewer VKT.	May improve the fuel efficiency of AVs on arterial spines.
Space & Space Use	Slightly less road space may be required than in Grid	More space may be required for roads.	A significant amount of road space can be reclaimed

Expected Benefit   Expected Threat   Uncertain

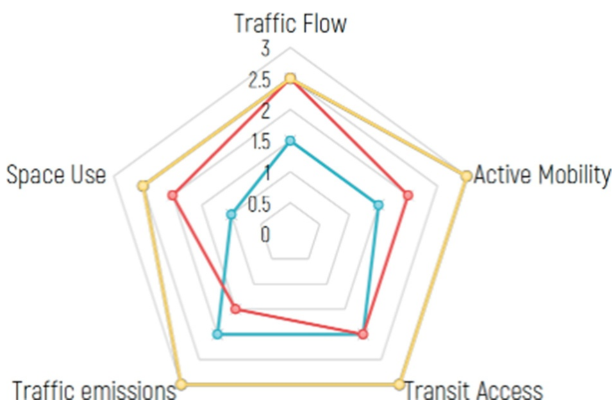

Figure 10. Comparison of performance of three network types.

could even result in more VKT. Finally, under some circumstances, the slowest network by speed can ironically have the fastest overall travel times.

First/last mile connectivity the biggest challenge with Loops

A hierarchical network with disconnected topology, as represented by the loops, does not perform well with dynamically routed small-sized shared vehicles. In the initial iterations, the smaller six-seater DRTs were not able to efficiently serve the network, with very high vehicle rejection rates.[1] On the other hand, a larger fleet size clogged the network and created congestion. After several iterations, small size vehicles were deemed unsuitable for the disconnected loop network structure, and larger 20-seater vehicles were deployed, while adjusting the number of vehicles so that the total number of seats available in all three models are similar. Despite these changes, the rejection rate for vehicles remained highest for Loops model.

The simulation results show a gap in first/last mile connection options for users in the Loops network. The DRT system is expected to fill this gap, but the high detour ratio resulting from the disconnected network topology does not allow this. This network has the highest in-vehicle travel time of all three network types (nearly 50% higher). The DRT mode share remains one of the lowest, and private car ridership is highest in Loops, as shown in Figure 11.

The travellers in Loops network prefer to use conventional scheduled buses or walk to their destination, as shown in Figure 11. The average walking time to transit in Loops is the longest at 8 minutes (about 400 m) which can be quite substantial for a tropical city like Singapore. Consequently, travellers shift to private cars as soon as they have it available as an option, leading to the highest vehicle kilometres travelled (VKT) by cars, taken as a proxy for traffic-based emissions here.

Loops network also loses out in terms of space consumption. More road space is required in Loops (250 lane kilometres) as compared to the grid (237 lane-kms) and superblock (167.5 lane km). Additionally, more space is also required for pick-up and drop-off activity since the DRT vehicles are larger in this model. Thus, it is very challenging to implement DRT as a first/last mile solution in a disconnected network topology.

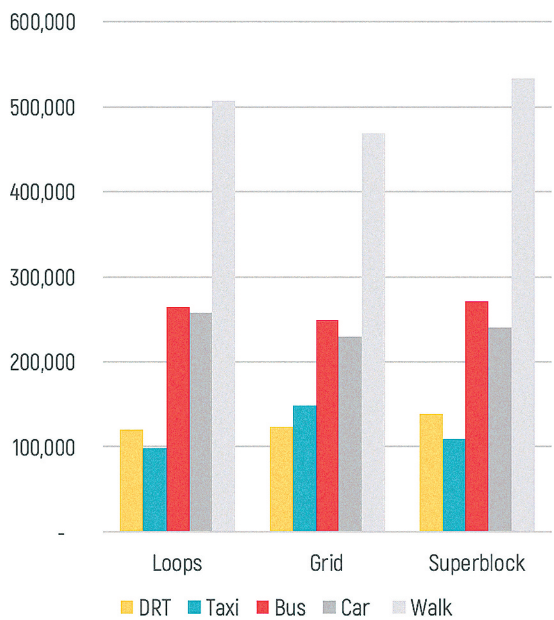

Figure 11. Comparison of trip legs by mode in all three network types. A trip is the direct travel between two destinations with one or more transport modes. An example for a trip is home to work. A trip leg is a segment of a trip, which is separated by a change of transport mode or an intervening stop with a short dwell time (e.g., stop for a coffee, public transport transfers).

The extra kilometres generated by the well-connected grid

The Grid network, as expected, provides better mobility for all modes by virtue of being better connected. The shorter detour distance would imply that a DRT system should function well in this network. But this was not found to be the case. Instead, private taxis were the mode of choice in Grid, accounting for 12% of all trip legs, the highest of the three networks, as shown in Figure 11. Taxis are so popular that they drive down the use of all other modes including, interestingly, private cars, which have the lowest VKT here of all three models. An unexpected outcome of short trips and high taxi use is the increase in waiting time for DRT, despite shorter travel distance. This may be because the taxi use is so high that even though fewer vehicles are available, users are willing to wait longer given the overall shorter travel times.

The high taxi use vis-à-vis car use can be explained by the fact that while car costs are sensitive to distance travelled, taxi costs are sensitive to travel time. Thus, if there is no congestion, taxi costs can be comparable to that of a private car, especially so with vehicle automation. In Singapore, taxis can be 600–700% more expensive than buses. However, with vehicle automation and electrification, the cost of taxi service is expected to go down (Bösch et al. 2018). Consequently, for shorter trips, a taxi can sometimes even be cheaper than a private car.

The high taxi use also drives down bus and walking trips despite much lower average walking time in a more connected grid. A connected topology is also expected to support bundling of pooled rides better and produce better occupancy rates in shared vehicles. However, when this is combined with taxis, the total distance-based occupancy of all shared vehicles goes down dramatically, even lower than in Loops, as shown in Table 2.

Can slower speeds lead to faster travel?

The Superblock functions well on almost all metrics. The slow traffic speed inside the superblock allows pedestrians to take shorter routes to transit stops. The improvement in walkability and pedestrian network has a much stronger effect on improving vehicle sharing and transit ridership, than creating a more connected traffic network topology. All shared modes perform well in Superblock, with the highest number of trip legs made with DRT, public transit and walking, as shown in Figure 11. When shared modes perform well, overall VKT generated is much lower than those in Grid (but still higher than Loops, since more trips are made overall). Empty VKT (shared vehicle cruising for rides or parking) remains the lowest in Superblocks.

It is interesting to note that the detour ratio is the smallest in Superblocks, even smaller than in Grid, even though the two have exactly the same network topology. This is an emergent effect that is not immediately apparent from the geometry of the urban form, and is a result of better ride bundling and higher occupancy rates in shared vehicles (DRT and buses) as shown in Table 2. This finding is counter-intuitive since superblock is a ‘slow’ network by design, with an average network free speed

Table 2. Distance-based occupancy of shared vehicles in all three networks.

	Loops	Grid	Superblock
Distance-based occupancy (DRT)	6.8	4.84	4.27
Distance based occupancy (DRT+Taxi)	2.83	1.99	2.08

Table 3. Observed traffic speeds during peak and off-peak hours on the three networks in the simulation compared to the designed network free speed.

	Loops	Grid	Superblock
Avg network freespeed*	42.77	41.30	29.03
Avg Network Peak Speed*	38.89	38.56	26.68
Length wtd Avg off-peak speed*	40.60	39.88	27.66
Avg peak speed/free speed	0.93	0.94	0.95
Avg off-peak speed/free speed	0.96	0.97	0.98

*Average of average speed on all links, weighted by link length.

lower than both Loops and Grids by almost 30%, as shown in Table 3. However, Superblocks have the best network performance, which is defined here as the average of the ratio of observed peak speed to free speed for every link. It is clear that the Superblock is slower, but not congested. This effect could be attributed to the Braess' paradox of traffic flow, a phenomenon where adding a new link to a transportation network does not improve the operation of the system, in the sense of reducing the total vehicle-minutes of travel in the system (Pas and Principio 1997), but this needs further investigation.

Conclusions from the experiment

Three main conclusions can be drawn from the results of this experiment. First, a connected network topology is generally beneficial to maintain traffic flow, but could be detrimental in the long run, generating induced travel demand, causing congestion and incentivizing private taxi use, especially when coupled with lower taxi fares due to vehicle automation. In order to tackle this issue, improvements in the active mobility network and a carefully considered pricing strategy for shared AVs must be prioritized.

Second, lowering the overall network speed could lead to improvements in average overall travel time for all users, with greater shared mobility and vehicle automation to ensure better speed compliance. Slow does not necessarily mean congested, but may in fact be a necessary measure for the overall rebalancing of the system.

Finally, last-mile connectivity, which has been challenging in New Town developments in Singapore, cannot be tackled solely by implementation of demand responsive transit as connections to bus and train stations. It is crucial to enhance pedestrian connectivity in order make shared mobility viable. The simulation results for the three network types in the experiment are summarized in Table 4.

Reflections on the proposed approach

Disciplinary integration between urban design and transport modelling has remained a critical challenge which is addressed here through a design experiment as a theoretical foundation. Models are simplified heuristically and in consultation with stakeholders, to reduce a large 'attribute space' to a limited range of values of interest, to create an ensemble of 'useful' models. Such simplified models can be run quickly in Sketch MATSim through a visual interface in, allowing a non-technical expert to test several design options. The design experiment presented

Table 4. Summary of results from the network experiment.

	Loops	Grid	Superblock
Traffic Flow	Traffic flow is hindered as a result of disconnected network	Traffic flow is good but network performance is not the best of all three models	This network is the slowest but performs the best in terms of the ratio of peak speed to free speed.
Active Mobility	The walk to transit access points and facilities is the longest, discouraging people from walking.	Walking time is shorter than loops, but total walking trips are lowest here, because of the attractiveness of private modes.	Shortest walking distance and most walking trips
Transit Access	DRT performance suffers due to detours and lack of connectivity, but bus performs slightly better	DRT usage is better here than in loops, but transit use is not so high	Shortest overall travel time and highest usage of DRT and bus
Traffic Emissions	Private cars generate high VKT but total VKT is not the highest	Lowest private car use but highest taxi use and high empty km generated, leading highest overall VKT.	Least empty VKT
Space & Space Use	More road space and PUDO space required	Slightly less space needed than in loops and lesser space required for PUDO	Least road space needed, but high PUDO space needed

Highest Score Lowest Score Medium Score

here illustrates how integrating simulations in design process adds the missing dimensions of 'time' and 'emergence', leading to new and often counter-intuitive findings, which cannot be fully understood through a purely geometric analysis (Batty 2018).

An added benefit of the building partial models is the collaborative process of identifying model parameters of interest collectively with the stakeholders involved in the design process. This grounds the research in practice and helps in managing the scope of research. At the same time, critical decision-makers and planners get an opportunity to 'rehearse the future' (Lyons 2015), by actively engaging in the research process, rather than being driven entirely by results produced by a black-box model.

Some limitations of the proposed approach must be acknowledged and compensated for in practice. These are related to the process of model definition, experiment evaluation and Sketch MATSim as a software.

Biases in model definition

This paper suggests to use heuristics to guide the process of model definition and experiment design. Such human-mediated design experiments enable a quantitative understanding to final design synthesis, but could lead to an undue focus on modelling attributes that are of interest to the stakeholder group involved in the process, under-representing the concerns of actors outside of it. To check this bias, only 'structural results' must be pursued through design experiments. Multiple answers should be encouraged for the same problem, without seeking a single correct 'solution'. As new stakeholders participate in the process, or new concerns emerge, subsequent experiments are expected to refute the conclusions of previous experiments. This is akin to a typical design process.

Building consensus among stakeholder to develop the design experiments and define performance measures is also challenging. Even if consensus on a set of assumptions is reached, it is always subject to change, following policy changes or new unforeseen developments within the span of the project. This challenge is tackled in part by buildings more agility into the tools and procedures used for both design and simulation. At the same time, design workshops can play a crucial role in building consensus, as much through the actual workshop outputs, as through the ethnographic methods of participant observation during the workshop. Multiple answers and hybrid solutions should be encouraged, without pursuing a single correct 'solution'. Design experiments were found to be a useful mediating object to elaborate contested visions and enable learning.

Issues in experiment evaluation

Deciding the level of detail to which a model is defined is critical. While a low level of detail is favoured to support quick iterative evaluation cycles, it must be acknowledged that if the model is too simplistic, the significance of the results might be compromised. The low level of detail may lead to results that are too close to each other, making it difficult to attribute them to any particular system effects. Additionally, the evaluation of the design experiments may rely heavily on quantitative data, which can create a positivist bias.

Other issues regarding model validation and calibration persist for agent-based modelling in general (Iacono, Levinson, and El-Geneidy 2008; Klügl and Bazzan 2012), and Sketch MATSim in particular. Validation helps determine whether an unexpected result of a simulation is due to the system dynamics or a programming mistake. According to Bankes (1993) the concepts of validation and sensitivity analysis are only relevant for consolidative modelling, and quality of exploratory modelling must be assessed based on ensuring the validity of the analytic strategy. Quality control issues are limited to verification that the model is plausible and that the software implements the model as intended.

Issues in Sketch MATSim

Sketch MATSim remains a tool under development, and a considerable amount of programming knowledge is still required to build the simulation model. Implementing new design strategies and policy measures (e.g., implementation of road pricing), requires technical intervention. Demand estimation, in particular, remains challenging since MATSim does not model travel demand endogenously, but needs exogenous estimation of travel demand choices. Further developments in Sketch MATSim are required to simplify the demand generation process with diverse land uses, for a non-technical user. However, as land use descriptions become more complex, this will become even more challenging without severely compromising computation time.

Future work

Usually, a stable path of technological development is assumed when developing predictive transport models. This assumption is unrealistic based on the trajectory of any technological development through history. Technology can fail, or new technologies can emerge in the long term, setting upon a completely different path. The global crisis triggered by the COVID-19 pandemic is such an example of societal disruption that can change the course of previously predicted developments.

Even as technological developments – within their physical, social, economic and environmental contexts – become increasingly uncertain, our design goals and intent remain relatively stable over time. Given this, the development of agile planning methods and tools that include time, emergence and human behaviour in analysis and representation becomes even more valuable than the outcomes of predictive models. An iterative two-way urban design and transport analysis workflow is essential to respond to such unexpected challenges and disruptions, technological or otherwise.

Note

1. When a user requests a DRT, the router searches for vehicles within 7 minutes' travel time from the user (this is pre-calculated based on link travel time in the previous iteration). If no vehicle can reach the user within 7 minutes, the DRT request is considered 'rejected'. Eventually, the user may have to wait longer than 7 minutes due to congestion. Rejection rates can be very high if there is a high level of congestion or low provision of vehicles.

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