# SimMobility: A Multi-Scale Integrated Agent-based Simulation Platform

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**ABSTRACT**

Developments in integrated agent-based platform has shown progress, however, most of efforts are based on integrating activity-based demand models with dynamic traffic assignment model. Integration beyond this level is limited and mostly based on loosely coupled mechanism (i.e. manual exchange of data). SimMoblity is a simulation platform that integrates various mobility-sensitive behavioral models within a multi-scale simulation platform that considers land-use, transportation and communication interactions. It particularly focuses on impacts on transportation networks, intelligent transportation services and vehicular emissions, thereby enabling the simulation of a portfolio of technology, policy and investment options under alternative future scenarios. In short, SimMobility encompasses the modeling of millions of agents, from pedestrians to drivers, from phones, traffic lights to GPS probes, from cars to buses and trains, from second-by-second to year-by-year simulations.

Simmobility is designed to support the activity-based modeling paradigm. All choices are ultimately tied to the agent's goal of performing activities on a time scale that can vary from seconds to years. Agents can be grouped in broad ways, from households to firms, and can have varying roles including operators, bus drivers or real-estate agents. Thus, the range of possible decisions is also broad, from travel (e.g. Mode or route choice, driving behaviour) to land-use (e.g. household or firm location choice).

This paper describes the SimMobility framework, its key features such as event-based implementation, parallel and distributed architecture and flow of data across three integrated levels. Additionally, application of the whole platform in Singapore context with some details on application of autonomous mobility on demand study is also presented.

# INTRODUCTION

In order to explore and evaluate future potential scenarios that involve new policies, infrastructure changes or even minor operational logic changes, simulation models are often the most reliable option. On the other hand, the complexity of all relevant interactions in a simulation model demands simplifications that often compromise the validity of the results. For example, in mesoscopic traffic simulation models, vehicle movement can be determined by representations such as speed-density relationship functions, with parameters calibrated a priori. While this provides reliable results under habitual circumstances, under new scenarios such as incidents or infrastructure changes, the demand or supply model assumptions might have changed. The use of decoupled models to solve this (e.g. using a microscopic model to obtain new parameters where/when needed) can be a challenging solution since it demands full consistency between models (e.g. mesoscopic and microscopic) and is often difficult to implement in practice. From this perspective, a fully integrated simulation model, that considers macro, meso and microscopic levels, is an ongoing challenge with significant impact for future research and practice. There has been some progress in developing integrated frameowrks, however, most of the efforts have shown loosely coupled integration between demand (usually activity-based model(ABM)) and supply (dynamic traffic assignment(DTA)) models. SimTRAVEL (*1*) shown a step ahead by inserting landuse component within integrated framework of ABM + DTA. Also POLARIS (*2*) has claim to provide more flexible agent based platform to integrate separate models together but so far has been applied only to a level of integration that can be classified as ABM+DTA. Development towards fully integrated platform that integrates long-term, mid-term and short term model together is scarce, primarily due to its challenging nature.

This paper present a fully integrated agent based platform named as SimMoblity which integrates various mobility-sensitive behavioural models within a multi-scale simulation platform that considers land-use, transportation and communication interactions. It focuses on impacts on transportation networks, intelligent transportation services and vehicular emissions, thereby enabling the simulation of a portfolio of technology, policy and investment options under alternative future scenarios. SimMobility incorporates three different sub-models:

• Short-term(ST) simulator - The time step can be a fraction of a second and agent decisions include lane changing, braking, accelerating, gap acceptance, but also route choice. SimMobility short-term model is a traffic micro-simulator (e.g. (*3, 4*)), extended with a communications simulator as well as pedestrians and public transport.

• Mid-term(MT) simulator - The time step is in the range of seconds to minutes and agent decisions include route choice, mode choice, activity pattern and its (re)scheduling, departure time choice. SimMobility mid-term is a mesoscopic simulator (e.g. (*5, 6*)), designed for activity-based modeling, with explicit pre-day and within-day behavior including re-routing and re-scheduling, and multiple transport modes.

• Long-term(LT) simulator - The time step is in the range of days to months to years, and agent decisions include house location choice, job location choice, land development, car ownership. It is a land-use and transport (LUT) simulator (e.g. (*7,8*)), with a market transaction bidding model.

This paper introduces the full SimMobility system, with focus on the innovative contributions that span across all levels. We emphasize the benefits and feasibility of a fully integrated approach, which relies, by design, on the acitvity-based modeling paradigm, with implications for all levels. The paper then disucsses the SimMobility through a case study with autonomous mobility which may have impacts on long-term, mid-term and short-tem levels, and is specifically designed to showcase advantages of integration across all thee levels .

## LITERATURE REVIEW

The concept of large-scale integrated models has long been recognized as a logical objective among urban and transportation planners. However, its complexity and high cost of research and development has also made a record of frustration that culminated, in 1973, with Douglas Lee's "Requiem for large scale models"(*8*). Our context today is quite different than in 1973, not just in terms of computational power but also in terms of data quality and quantity, essential for calibration (*9*). It is thus without surprise that we now see a new wave of research in large-scale integrated models.

The common approach is through loose coupling of different models, each one specialized on a component. The interface between models consists of exchanging files or API (Application Programming Interface) calls. Majority of the recent efforts are concentrated towards integrating activity-based models with dynamic traffic assignment models in an agent-based framework. The demand component of these integrated models attempt to simulate the daily activity schedules of each individual (considering travel decision such as day pattern, mode, route and departure time choice for activities in a day). These activity schedule then passed on to the supply model, which execute their daily schedules in relation with the transport network. During the process network travel times are updated and feedback to the demand component. The iterative process is used to brings consistency between the two models. Among these efforts most notable are integration of CEMDAP (an ABM) with MATSIM (*10*). CEMDAP (Comprehensive Econometric Micro-simulator for Daily Activity-travel Patterns)(*11*), focused primarily on activity scheduling. MATSIM (*6*) on the other hand, in its own assumes individuals initial plans of the day which are derived on the basis of the household survey data. These initial plans are then executed in MATsim demand-supply simulator and, based on the score, agents adapt their plans in response to conditions that arose during the simulation. The scores within the MATSim are based on heuristic utility functions with a limited set of variables, mostly network performance related. The new plans are generated based on iterative feedback mechanism by modifying few scheduling dimensions of initial plans in order to get a stable solution, which they called a schedule user equilibrium (*12*). The integration of CEMDAP with MATSIM provide a framework which is more richer in terms of incorporating behavioural notions of individual travel decisions. The challenge is then to make these models speak with each other and guaranteeing full consistency. Moreover, it is difficult to implement just-in-time feedback processes such as activity rescheduling due to within-day dynamics. For example, in a major disruption scenario, many agents will need to reschedule/cancel their upcoming activities on a non-user equilibrium basis, i.e. with partial awareness of the options and of other agent's decisions. Another example of such an integaration is based on the framework named as FEATHERS(*13*). In a study in the Flanders region of Belgium, it was connected with

ALBATROSS(*14*), which provides it with daily activity schedules for the entire population using a rule based paradigm. Further, and have other components that model rescheduling decisions, in relation with supply side. Again, some effort is needed to combine the models together and make them spatially and temporally consistent(*15*).

While, in general, the approach has been to combine two or more sophisticated models on a loosely coupled fashion (e.g. activity-based demand simulator with a dynamic traffic assignment model), some models exist that are developed on the notion of integrated framework that can simulate full day activity/travel schedules. TRANSIMS (*16*) is an earlier example of such integrated model. There exist four distinctive modules in TRANSIMS such as Population Synthesizer, Activity Generator, Route Planner and Microsimulator. The Activity Generator module in TRANSIMS uses collected household survey data to work out almost all scheduling dimensions of activity patterns of synthetic individuals using some rules, random selection and matching of few socio-economic characteristics of individuals from the survey. Further within TRANSIMS, there is a feedback mechanism introduced between Router and Microsimulator, which attempts to bring the system into equilibrium. However, during that process, individuals can only change their routes with no flexibility of changing other dimensions of their activity patterns. Later, MATSIM was developed on similar notion as TRANSIMS, and both have been used with ABM to overcome the lack of behavioural richness.

In addition to the efforts of integrating demand and supply models of day level travel decisions, some efforts are found in the literature where long- term decision models are loosely coupled with day level travel decision models. For example, Urbansim combines land-use, demographic and business establishment models, where agents make long-term decisions (e.g. home and job relocation) by considering, among others, transport accessibility (*17*). A common approach to obtain accessibility measures is by calling travel models, such as Transcad (*18*), which runs a 4-step model, TRANSIMS(*19*), or MATSim(*20*), the latter two following an activity-based paradigm. Very recently, an integrated modeling system, SimTRAVEL (Simulator of Transport, Routes, Activities, Vehicles, Emissions, and Land) is presented with a view to more tightly tie together long terms and mid-term level decisions (*1*). SimTRAVEL claimed to integrate three separate model in a unified framework, these are Urbansim (landuse model), OpenAMOS (ABM) (*21*) and MALTA (DTA) (*22*). The design structure of SimTRAVEL gives much emphasis on integration of OpenAMOS and MALTA, and Urbansim model is loosely coupled by providing network travel times based accessibility measures to simulate location choices for the next year. Most of the case studies reported using SimTRAVEL are also based on application of OpenAMOS and MALTA. Berryman et al (*23*) argued that absence of microscopic traffic simulator in SimTRAVEL does not allow to test cases which require capturing of dynamics at a sufficiently low level of scale, such as impacts of different light rail transit alignments on traffic and landuse patterns.

Another notable and very recent effort in the area of integrated framework is POLARIS (Planning and Operation Language for Agent-based Regional Integrated Simulation), which build on the notion to provide platform within which several separate models are plug-in together to provide integrated agent-based platform. So far, the use of POLARIS is limited to integrate only ABM and DTA models i.e. an integration of ADAPTS (*24*) and a mesoscopic traffic simulation model with a special focus on carrying out intelligent transport based case studies. Auld et al (*2*) reported priliminay results of one such study for Chicago region. According to Hope et al (*25*), the design of POLARIS is such that it incorporates innovative computaitional methodologies to make sure integration of different models is intact and at the same time provide high performances. However, there are no notable examples and results mentioned in support of these claims.

The literature review clearly indicates that integrated modeling framework is still an emerging field, and so far successful integration modeling examples are limited to combine ABM and DTA models. The recent efforts are attempting to integrate long term models with ABM and DTA, however, the integration is mere on the basis of exchanging data files. This paper reports development of fully integrated SimMobility framework, that is developed primarily to integrate Long-term (land use models), mid-term (ABM+DTA) and short-term (microscopic traffic model) in unified framework. Within long-term it utilized Urbansim, at mid-term it utilses day-activity schedule approach with DYNAMIT as its supply side and the short term is using MITSIM at its base. The main objective was to provide a platform which enables the simulation of a portfolio of technology, policy and investment options under alternative future scenarios, where impacts of the scenario can be visualized at its three levels in a consistent manner.

## SIMMOBILITY FRAMEWORK

SimMobility is conceived as a multi-level, integrated, activity based modeling platform. It is **multi-level** because it comprises three different simulators: the ST simulator represents high spatial temporal resolution (i.e. in the order of tenth of a second) events and decisions, such as lane-changing, braking and accelerating, individual and crowd pedestrian movement, agent to agent cell-phone communications. The MT simulator represents daily activity scheduling, mode, route, destination and departure time choices on a multi-modal network. Its temporal resolution is in the order of seconds or minutes. The LT simulator represents long-term choices such as house and job relocation or car ownership. SimMobility is also **integrated** because it simultaneously simulates demand and supply at each level, as well as interactions between different levels. Figure 1 reflects these interactions. SimMobility is designed using **activity-based** modeling paradigm. The LT simulator is influenced by activity-based accessibility measures, which are provided by the MT. The MT demand model is a full-fledged activity-based model, that incorporates pre-day activity-scheduling together with destination, departure time, route and mode choice (and rescheduling and re-routing during the day). The ST model receives trip-chains and activity-schedules as inputs and can also do re-routing and activity plan changes in simulation run time. Each of the three levels is modular and autonomous, and we can apply each one in isolation, by providing the appropriate inputs. I.e., the tight coupling is not mandatory. On the other hand, to take full advantage of its potential, SimMobility demands a tight coupling integration. For example, consider a policy scenario where an area is restricted to autonomous vehicles. The original macroscopic fundamental diagrams may no longer apply at the MT level simulation, which would demand running simulations at the ST level (to capture the updated performance parameters). At the MT level, plenty of changes would be observable in the restricted and neighbour areas due to mode shift, new routes, destination and activity choices. This would imply new accessibility measures, with implications for the LT. All of these feedback loops would occur multiple times in SimMobility .

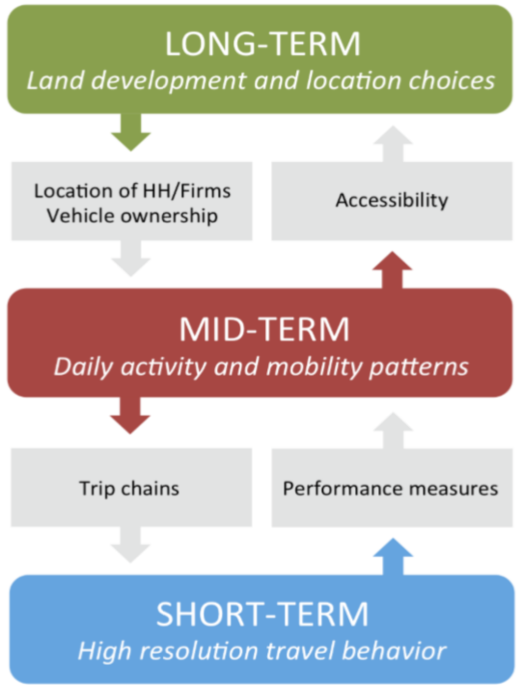



**Figure 1: SimMobility Framework**

As a second example, let's consider a major disruption due to an accident/harsh weather/road blockage. Agents would need to opportunistically reschedule and/or re-route. This would deem available network performance parameters invalid in focus areas, and demand ST level simulation. At the MT, agents would need to do within-day re-routing and rescheduling. As a one-time event, it wouldn't affect the LT, however one could use SimMobility as a scenario exploration tool: "what network/land-use characteristics would bring more network resilience in such events?". In this sense, SimMobility could allow multiple runs with multiple parameters at the LT level.

Both scenarios involve interactions between different levels and between supply and demand models, at different moments in time. While it is in theory possible to use the loose coupling approach for combining different available models, to our knowledge none is designed to implement these cases without considerable adaptation. In terms of its software design, SimMobility relies on three concepts: one database shared by all models; a hybrid simulation mechanism, with demand being event-based and supply time-step based; a parallel and distributed architecture.

**One database**

The same database is shared by all levels. This implies that our modelling platform keeps track of household, and individual preferences and choices across levels: an agents' specific long term attributes, such as car ownership, is linked to her/his mode availability at the MT and eventually to individual driving behavior attributes specification, such as reaction time or desired speed. In this way, one can model demand consistently at the disaggregate level, keep track of a multi-level individualized history, and avoid complicated book-keeping necessary to maintain consistency of loosely coupled models. SimMobility's database is fully implemented in a Postgres SQL database, which works on relational paradigm.

### Event-based demand, time-step supply

Agents need only be active when they make decisions, which happens when triggered by their perception. The perception is represented as the reception of an event information that is relevant for the agent. An event can be “arrival at intersection", “arrival at the destination bus stop", “taxi in sight", “trip delay greater than threshold", “changes in current job/school for kids", “changes in neighbourhood accessibility", etc. Thus, there can be events at any level of SimMobility. To implement these events, we use a publish/subscribe mechanism where agents subscribe to potential future awakening events before getting into an auto-pilot mode. This auto-pilot mode is where agents spend most of their simulation time: each decision that is made (e.g. route choice, relocation choice, execution of an activity) is translated into a plan that is executed by the simulator. Until this plan is complete or a subscribed event occurs, the agent is in the auto-pilot mode. Figure 2 represents the simulation cycle of our agents in each of the levels.

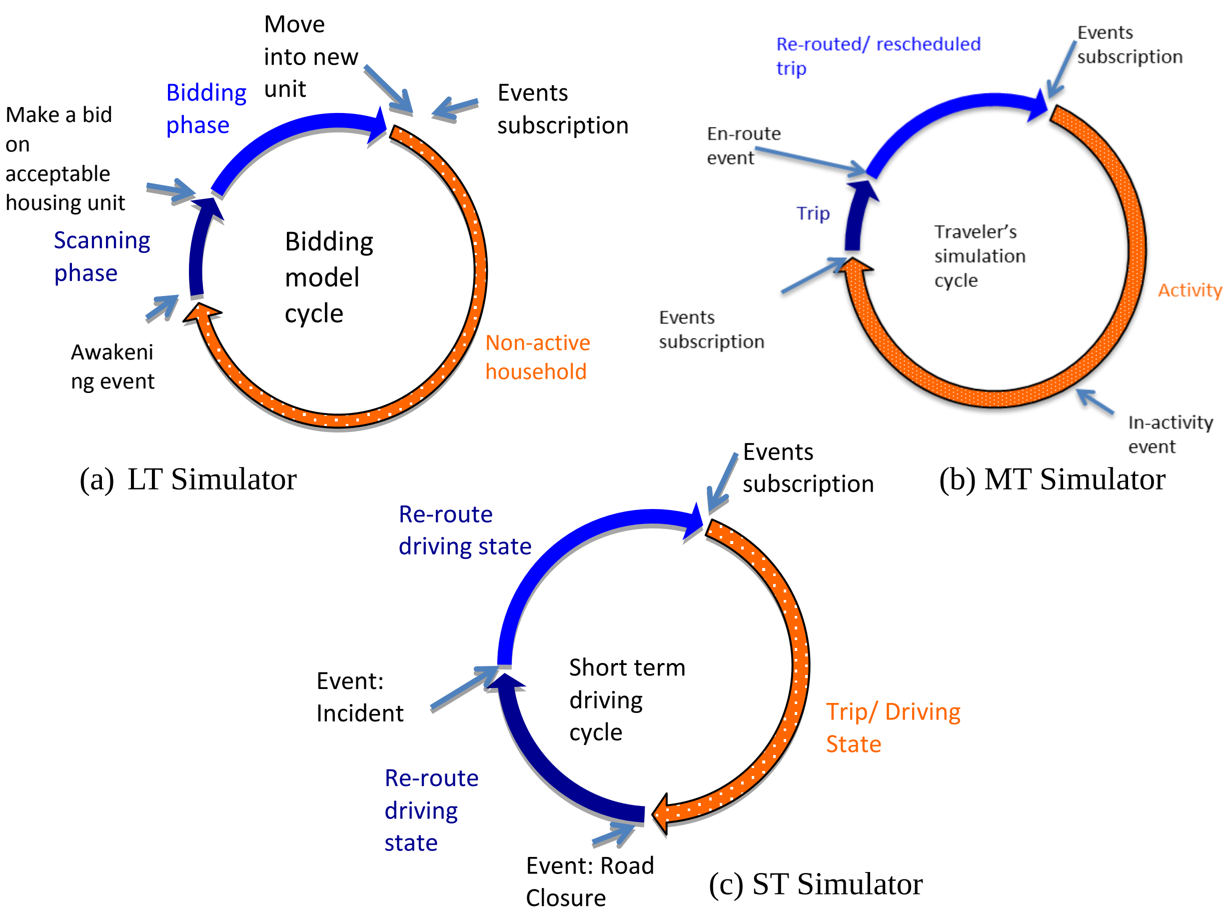
In the LT, real estate transactions model, a household will be non-active (auto-pilot) most of the time until some event (e.g. a job change or launch of new household estates) wakes it up. It will then enter a state of scanning the market for suitable housing. If the household finds potentially suitable housing among the listings, it will enter a bidding process with the sellers until converging to a choice or giving up (for at least several months). During the scanning and biding phases, there may be multiple message exchange events between the sellers and the households. At the MT level, agents will be sensitive to events both during activities and during trips. Such events may trigger rescheduling decisions, re-routing, early starting of trips (e.g. activity ends abruptly due to weather; due to emergency situation) or any other decision that is modeled in the system. Similar to MT, the ST uses same notion e.g lane/road closure at particular point in the road network. An agent that subscribed this event, may react to this and re-route well before reaching to closure point, where only limited options are available.

In practice, this mechanism allows for computationally very efficient interaction between supply and demand. The supply side, always time-step based, simply picks the latest plan information for each agent and executes it. A global events manager module, checks at each time step, which subscribed events occur and wakes up the respective agents. If the agent changes its plan due to an event, it will be reflected for the next time step, which will be executed by the supply simulator. This publish/subscribe mechanism is fundamental for opportunistic activity scheduling, as suggested in (*24*). For example, an agent could subscribe to an event to "wake him up if he’s 5 minutes to a supermarket".

### Parallel and distributed architecture

SimMobility is entirely developed in C++, using boost threads library, for parallelization, and MPI (message passing interface) library, for distribution. It is able to do runtime load balancing by taking advantage of individual agent’s context (e.g. neighbor agents can be grouped together; agent of similar type can be grouped together). It also allows network decomposition with MPI distribution. Sim Mobility achieves parallelism by separating Agents into multiple worker and then running through each Worker's list of agents in parallel. Essentially, the millions of agents of SimMobility will be computed in parallel by many instance of the simulator on different processors. Put together, SimMobility takes advantage of state-of-the-art computational efficiency tools to increase scalability.

We will now describe in more detail each of the three SimMobility levels. This paper aims to present the general framework, with emphasis on the inter-level interactions, the benefits and challenges of a fully integrated approach. We will occasionally redirect the reader for available and upcoming literature for further details.



(a) LT Simulator (b) MT Simulator (c) ST Simulator

**Figure 2: Events simulation cycles in relation with three Simulators**

## LONG-TERM SIMULATOR

The long-term (LT) simulator of SimMobility models the behaviors of agents in the housing market, and ultimately the commercial real estate market and the job market, in order to simulate the yearly and longer term impacts of alternative future mobility scenarios on residential and workplace locations; vehicle ownership; the density, land use distribution, and value of the built environment. Figure 3 shows the framework of the LT simulator. In general, the LT simulator is responsible for the generation and updating of a population of agents and their corresponding demographic and locational attributes. In the beginning, a two-stage data synthesis methodology is employed for construction of a synthetic population of households and firm establishments at building scale. The approach is designed to accommodate the need for spatially disaggregated details in a manner that can be readily adjusted and rerun to incorporate new data sources, changed time frames, and updated relationships and hierarchies across overlapping datasets. Long-term behaviors of agents and their effects on urban form, markets and other agents are implemented by a group of behavioral models that are connected in a sequential/event-based framework.

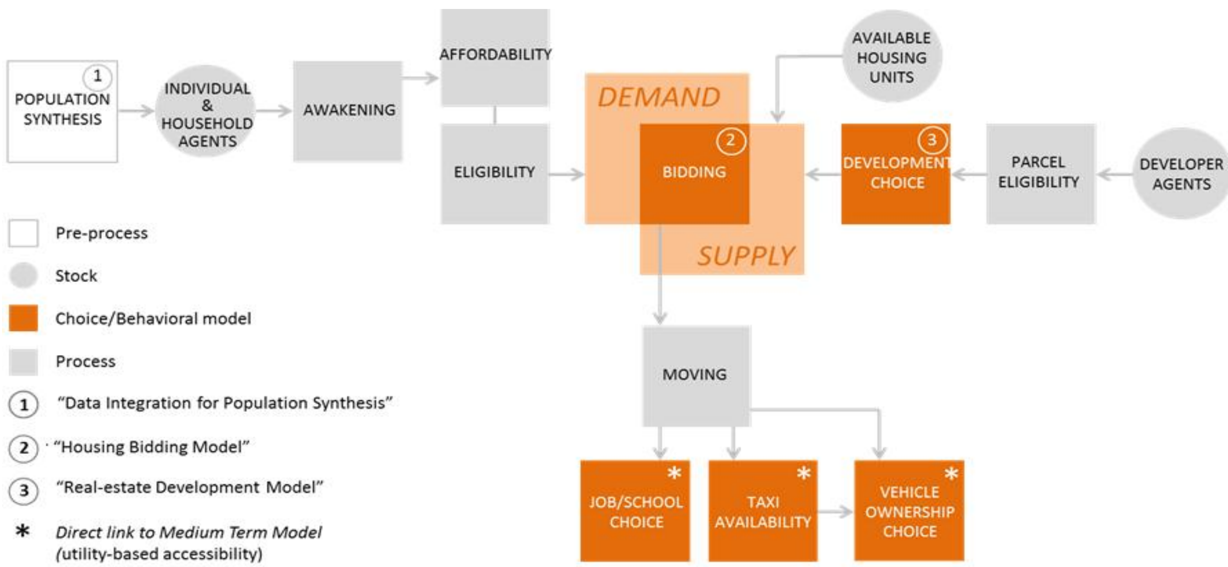



**Figure 3. Framework of the Long-Term Simulator**

These behavioral models take account of demographic and economic factors of agents, locational amenities and the regulatory variables translated from exogenously specified policies. The LT simulator centers on a real estate market module, which emulates the dynamic interaction process between demand and supply in the market. The market module include a series of models that simulate (a) 'awakening' of households who begin searching for new housing, (b) eligibility, affordability, and screening constraints, (c) daily housing market bidding, and (d) modeling developer behavior regarding when, where, what type, and how much built space to construct by taking into account market cycle and uncertainty. Changes in residential location then trigger a household's re-assessment of private vehicle ownership and possible re-assignment of workers (students) to jobs (schools).

The long-term simulator is integrated with the MT simulator via built-in functions facilitating the exchanges of data that characterize the status-quo of land use and transportation performance. One set of functions computes accessibility measures for individuals considering alternative residential, work, or school locations, and alternative vehicle ownership conditions. These measures can be computed quickly since they vary the circumstances of only the one individual. Another set of functions allows the LT simulator to pass population (and firm) information with updated residential and job locations as well as vehicle ownership. This information is sent periodically so that the MT simulator can reassess overall activity patterns and accessibility conditions, and the

LT simulator can then make choices based on adjusted expectations accessibility. Currently this exchange is done annually. Information on the performance of transportation services and activity-travel participation of agents is fed to the land use module of SimMobility (i.e. the LT simulator) through a utility-based, behaviorally rigorous accessibility measure, the *logsum*. It is the expected maximum utility of a person in a series of activity related choice situations.

In SimMobility, the *logsum* measure reflects the range of choices in destinations and modes, the scarcity of time and money, and accounts for the heterogeneous preferences among agents. Therefore, it is a link between the MT simulator and the LT simulator which ensures the behavioral consistency of agents by encapsulating agents' day-to-day activity and travel considerations into their long-term location and vehicle ownership choices. However, because the *logsum* measure is individual specific and not directly comparable across agents, it is first converted to cost (dollars) before being aggregated in the LT simulator to model household-level choices.

**MID-TERM SIMULATOR**

The mid-term (MT) level simulates daily travel at the household and individual level. It is categorized as a mesoscopic simulator since it combines activity-based microsimulator on the demand side with macroscopic simulation at the supply side. Figure 4 presents the modeling framework of the MT simulator implemented in SimMobility. Detail description of each component of the MT model can be found in (*26*). The demand comprises two groups of behavior models: pre-day and within-day. The pre-day models follows an enhanced version of econometric Day Activity Schedule approach (presented in (*27*)) to decide an initial overall daily activity schedule of the agent, particularly its activity sequence (including tours and sub-tours), with preferred modes, departure times by half-hour slots, and destinations. This is based on sequential application of hierarchical discrete choice models using a monte-carlo simulation approach.

As the day unfolds, the agents apply the within-day models to find the routes for their trips and transform the activity schedule into effective decisions and execution plans. Through the publish/subscribe mechanism of event management, as mentioned above, agents may get involved in a multitude of decisions, not constrained to the traditional set of destination, mode, path and departure time depending upon their state in the event simulation cycle. For example, the agent could reschedule the remainder of the day, cancel an activity (or transfer it to another household member), re-route in the middle of a trip (including alighting a bus to change route), or run an opportunistic activity, like shopping while waiting. The supply simulator follows the dynamic traffic assignment(DTA) paradigm as used previously in DynaMIT (*5*), including bus and pedestrian movements. Particularly for public transport, MT model allows for bus (and subway) line scheduling and headway based operations are currently being implemented. We also explicitly represent on-road bus stops and bus bays both at the mid-term and short-term, which allows for accurate estimation of impacts of the bus operations on the road traffic. Within the MT simulator, the interaction between the within-day and supply is responsible to bring the system to consistency. In addition to this, a day-to-day learning module, which feeds back network performance to the pre-day model, is introduced to update agent's knowledge (either as a calibration procedure or for a multiple day simulation).

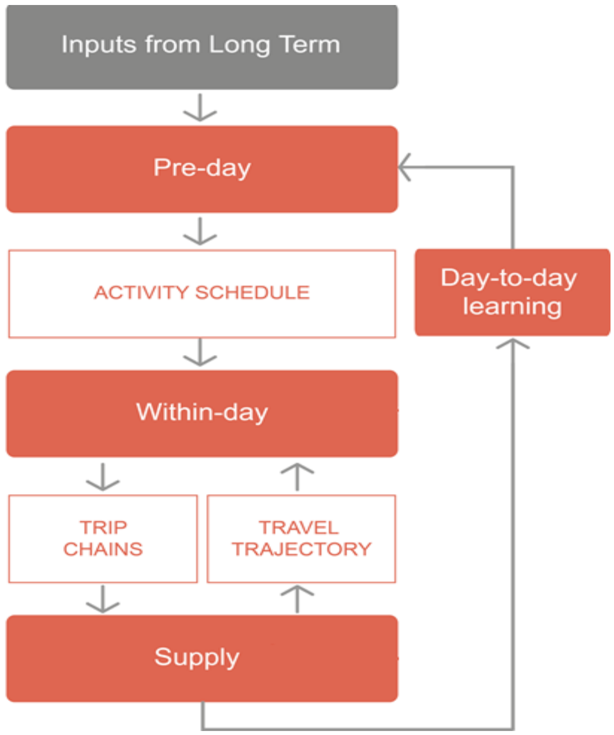



**Figure 4: SimMobility Mid-Term Model**

The MT simulator takes input in the form of population (an output of the LT level) that contains details characteristics of each agent in the simulation region, and process the day activity schedule of each agent. Furthermore, it passes the accessibility measure in the form of logsum from the top-level model of preday component to the LT simulator representing maximum expected utility of activity-travel pattern at given supply conditions. The MT simulator also passes trip chains to ST simulator as a demand to simulate smaller region traffic with microscopic details.

## SHORT-TERM SIMULATOR

The short-term(ST) simulator is an agent-based, multimodal microscopic simulator where agents' movements are captured at a very fine resolution (up to 100 milliseconds). ST comprises three main component (see Figure 5).

This microscopic traffic component is responsible for advancing drivers, pedestrians and goods on the transportation network according to their respective behavioral and decision models. It is based on an open-source microscopic traffic simulation application named as MITSIM (*3*)). Several enhancements were made to the MITSIM original driving behavior such as: an enhanced reaction time formulation capable of explicitly model reaction time and perception delays for each person(*28*); lateral movement during lane-change and within lane and also intersection behaviour model, which is based on the conflicts technique. The Control and Operation system simulates the control centers, such as traffic and parking control, bus control, rail control, logistic control, etc. In addition this module is responsible for controlling the operations of a fleet of autonomous (or self-driving) shared cars, an application of this is presented in (*29*).

The third component is the Communication network, which simulates agent-to-agent communications. Information can be passed from one agent to another via the mobile communication or via vehicle-to-vehicle communication or via vehicle-to-infrastructure communication. The Communication network simulator is responsible for simulating the physical communication network (for example, a wireless network), and agents simulated within microscopic traffic network will use this simulated network to pass information between them. This gives agents access to a realistic communication network, which handles the message delivery delay and coverage as presented in (30).

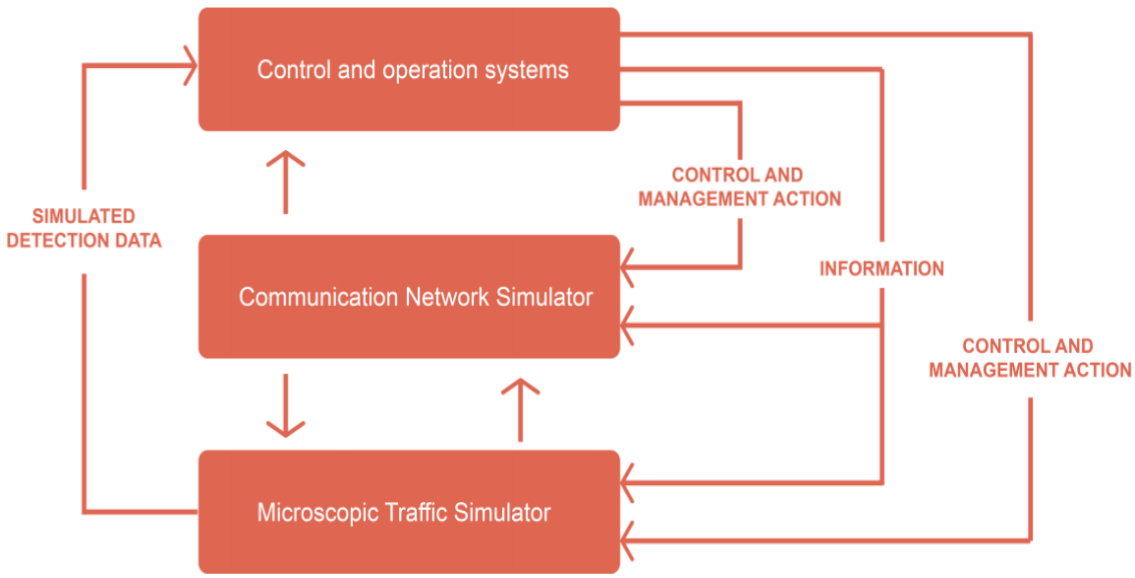



**Figure 5: SimMobility Short-Term Model Framework**

For perfect integration with higher levels of SimMobility, instead of the traditional O-D matrices, ST uses an activity based demand formulation in the form of trip chains (generated through an individual activity schedule, which is an outcome of MT simulator). Furthermore, the input system is flexible enough to work with O-D matrices if ST is used as standalone, thus simultaneously keeping the modularity of the whole framework. In similar fashion, the structure of the outputs in the form of performance measures (such as travel times) is such that it can be easily transferred to MT for further processing. This is one of the key feature of the case study of autonomous mobility on demand performed using SimMobility.

## CASE STUDY: AUTONOMOUS MOBILITY ON DEMAND

We have applied SimMobility to a case study in Singapore. The models in LT simulator as explained above are estimated using various data sources such as the postal code based landuse data, firm locations and thier characteristics, School locations and its enrollments, and household interview travel (HITS) survey collected in 2008 in Singapore. Within the MT simulator, preday component is modelled utilizing the HITS along with some additional data on dynamic origin-destination based skim matrices used primarily for mode choice and time-of-day decisions. Private and public route choice models in within-day component, which are coupled with supply simulator to perform DTA, are estimated using taxi GPS data and smart-card data (EZ-link card). The supply component of the MT simulator uses the speed-density relationship, and is calibrated for singapore road network. The ST model also utilized various data sources (intersection counts data, traffic light data) from Singapore to calibrate the microscopic model parameters such as lane-changing, car-following and intersection behavior models. Furthermore, the base case the ST model is also calibrated for extended CBD region of singapore to replicate the observed measures of detailed network performance indicators. The results produced for the base case using the full synthetic population of Singapore by application of all three levels are plausible and required reasonable run-time as shown in Table 1.

**Table 1 : Performance of three levels of SimMobility**

| *SimMobility Level* | *High Peroformance Cluster Machine (No. Of threads)* | *Population Size/ Network Size* | *Hours/day simulated* | *Simulation Run Time* |
|---|---|---|---|---|
| LT | 100 threads | 1.15 million household | One year | 12 hours |
| MT | 6 threads | 4.06 million indivdual/ Singapore Road network | 1 day | 12 hours |
| ST | 15 threads | 0.06 million drivers, for CBD network of 14 square-km | 12 hours | 1.25 hours |

Ideally a linear speedup can be achieved running the simulator on N processors can complete it in 1/N amount of time if there is no interaction between the agents. But in reality a simulator needs communication and synchronization between the agents which slow down the simulator. In LT simulator, agents require less communication between the agents as they are at household level and household take decision independently without depending on the other household. So greater performance can be achieved by distributing the households in multiple threads and running them in parallel. But mid-term and short-term has high degree of inter-agent data dependency and it require agents to communicate and synchronize at each time-step with each other to move in the simulation. So in this case more threads will bring more overhead and the performance actually degrades once the number of threads goes beyond the optimized number of threads. We are in the process of optimizing the performance by using graphics processing units (GPUs), efficient data structure and also by network decomposition across the multiple machines.

This particular case, a policy scenario with AMoD, is the subject of a related paper, under review(*31*). For further details on this analysis, literature and results, we kindly redirect the reader to that document. The case study utilizes SimMobility MT and ST simulator in an integrated manner. Efforts to integrate LT and find out impacts of this scenario on landuse are currently ongoing. In our case scenario private vehicles are not allowed to access a $14km^2$ restricted zone in the Central Business District (CBD) of Singapore and an AMoD service was introduced as an alternative mode. The AMoD service can be viewed as a smart-phone service based on shared on-demand autonomous taxis. The restricted zone may still be accessible by the existing bus lines, MRT, taxis and by walking. For example, a traveller riding a private vehicle, who works within the restricted zone and lives outside it, must park her/his vehicle outside the area and continue her/his journey using AMoD.

Using the ST, which contains the AMoD service controller, different fleet sizes for the AMoD service were tested and the waiting and travel times within the restricted zone were analyzed by taking the demand in the form of trip chains from the MT simulator. In doing so, ST simulator were given the demand only for the restricted zone. This was done by dividing the private vehicle trips, which were destined or originated in the CBD region and have their origin and destination outside the CBD region into two sub-trips, i.e. one sub-trip is inside the CBD region and the second one is outside the CBD region. The inside CBD sub-trip is simulated using AMoD service. This is also true for those trips who have their origin and destination within the CBD region. The obtained travel times on the links for the scenario, were transferred back to the MT simulator, where these travel times for the inside CBD sub-trip is combined with outside CBD sub-trip (obtained from the supply of MT) and stored in a manner that it can be aggregated and feedback to the pre-day component of the MT. The preday model assumes private vehicle trips as a combined modal trip (i.e. Private vehicle + AMoD) if part of the trip is inside CBD. This is done by modifying the utility specification of private vehicle mode in the mode choice model by adding the waiting time and additional cost terms. Further parking prices for private vehicle is reduced as now they have been parked outside the CBD region. The cost of the AMoD part of the trip is considered 50% lower than the similar taxi trip. Additionally, the within-day component of MT, route choice for the private vehicle trips whose origin and destination was outside the CBD region was performed considering the unavailability of routes through the CBD region. With these assumptions, several iterations were run in between the two simulators for consistency. This integration allows us to consider the impacts of introducing AMoD within the CBD region for an entire Singapore transportation network, along with behavioral changes in the individual’s activity schedules. Our results show a significant change in the travel pattern due to this scenario, e.g.: commuters destination choice for some trips changed, as some travelers showed preference to shop outside the CBD; the restricted zone affects route choice of through traffic and the performance of the road network.

## CONCLUSION

In this paper, we gave an overview of the SimMobility project, an integrated activity-based model that is being developed in the Future Urban Mobility integrated research group of the Singapore-MIT Alliance for Research and Technology (SMART/FM). Its software architecture is designed to be massively parallel and distributed, allowing for ready scalability and fast simulation. SimMobility is an integrated simulation tool for evaluating potential technology, policy and investment options under alternative future scenarios. We discussed the benefits and challenges of such an approach and presented an example where SimMobility levels interact to study a scenario of Autonomous Mobility on Demand (AMoD).

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