

1 **SimMobility Short-term: An Integrated Microscopic Mobility**

2 **Simulator**

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Carlos **Lima Azevedo**
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139, USA
Phone: +1 6174522482
Fax: +1 6172531130
email: cami@mit.edu

Harold **Soh**
University of Toronto
27 King's College Cir, Toronto, ON M5S
Phone: -
Fax: -
email: harold.soh@utoronto.ca

*Simon **Oh**
Singapore MIT-Alliance Research and Technology
1 Create way, 138602 Singapore
Phone: +65 66012828
Fax: +65 6684 2118
email: simon@smart.mit.edu

Kakali **Basak**
Singapore MIT-Alliance Research and Technology
1 Create way, 138602 Singapore
Phone: +65 66011634
Fax: +65 6684 2118
email: kakali@smart.mit.edu

Neeraj Milind **Deshmukh**
Singapore MIT-Alliance Research and Technology
1 Create way, 138602 Singapore
Phone: +65 66011634
Fax: +65 6684 2118
email: neeraj@smart.mit.edu

Tomer **Toledo**
Technion - Israel Institute of Technology
Haifa, Israel
Phone: +972 48293080
Fax: +972 48295708
email: toledo@technion.ac.il

Balakumar **Marimuthu**
Singapore MIT-Alliance Research and Technology
1 Create way, 138602 Singapore
Phone: +65 66011634
Fax: +65 6684 2118
email: balakumar@smart.mit.edu

Li-Shiuan **Peh**
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139, USA
Phone: +1 6173248428
Fax: -
email: peh@csail.mit.edu

Katarzyna **Marczuk**
Singapore MIT-Alliance Research and Technology
1 Create way, 138602 Singapore
Phone: +65 66011634
Fax: +65 6684 2118
email: katarzyna@u.nus.edu

Moshe E. **Ben-Akiva**
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139, USA
Phone: +1 6172535324
Fax: +1 6172531130
email: mba@mit.edu

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6 * Corresponding Author: simon@smart.mit.edu

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1 **ABSTRACT**

2 In this paper we present the development of an integrated microscopic mobility simulator,
3 SimMobility Short-Term (ST). “Integrated” as its models, inputs and outputs, simulated components and
4 code-base are integrated within a multi-scale agent- and activity-based simulation platform capable of
5 simulating different spatial-temporal resolutions and account for different levels of travelers’ decision
6 making. “Microscopic” as both the demand – agents and its trips – and the supply –trip realization and
7 movements on the network – are microscopic, i.e. modeled individually. Finally, “Mobility”, as it copes
8 with the multimodal nature of urban networks and the need for the flexible simulation of innovative
9 transportation services such as on-demand and smart mobility solutions. This paper follows previous
10 publications that describe SimMobility’s overall framework and models. SimMobility is a multi-scale
11 platform that considers land-use, transportation, and mobility-sensitive behavioral models. SimMobility ST
12 aims at simulating the high-resolution movement of agents (traffic, transit, pedestrians and goods) and the
13 operation of different mobility services and control and information systems.

14 This paper presents SimMobility ST modelling framework and system architecture, reporting its
15 successful calibration for Singapore and its use in several scenarios of innovative mobility applications. We
16 also show how detailed performance measures from SimMobility ST can be integrated with a daily activity
17 and mobility patterns simulator. Such integration is crucial to accurately model the impact of different
18 technologies and service operations at the urban level, as the identity and preferences of simulated agents
19 are maintained across temporal decision-scales ensuring the consistency and accuracy of simulated
20 accessibility and performance measures of each scenario.

21
22 **KEYWORDS**

23 Keywords: microscopic simulation, traffic simulation, activity-based models, mobility,
24 communication networks
25

1 INTRODUCTION

2 Microscopic traffic simulation applications are now part of the daily transportation planning and
3 operation realities. In order to explore and evaluate complicated future transportation scenarios, we need to
4 conduct experiments. Physical experiments can be conducted in order to understand how the different
5 options work together on a small scale. For the entire urban area, however, a simulation model is the only
6 viable option. Microscopic traffic simulation models have been widely used to test different road network
7 and ITS solutions. They aim at replicating detailed vehicle motions and interactions by modelling agent
8 decisions such as route choice, accelerations, decelerations, and lane changes. These models are
9 implemented as synchronous applications that update the kinematic parameters of each entity (driver-
10 vehicle units, public transportation, management systems and even pedestrians) at every simulation time
11 step. Similar to other transportation simulators, the design of microscopic models is based on a demand and
12 supply equilibrium representation. Traffic demand input is formulated either by defining it in terms of input
13 flows and turning proportions at intersections or, for larger networks, in terms of origin–destination (OD)
14 matrices that will rely on route-choice models for network assignment [1]. An example of these simulators
15 are AIMSUN [4], VISSIM [5], Q-Paramics [6], Tansmodeler [7], ARTEMIS [8], CORSIM [9], DRACULA
16 [10], HUTSIM [11], Integration [12], MITSIMLab [13], SUMO [14], Cube DynaSIM [15]. The first four
17 simulation tools belong to the short group of integrated platforms available for fast implementation and that
18 have been successfully used in a variety of transportation projects, accounting for a share of more than 70%
19 of the practitioners and researchers preference [16].

20 In microscopic traffic simulation, the supply implementation relies on the specification of the
21 network configuration, the traffic management algorithms and the driving behavior model. From the initial
22 models developed in the 50’s for car-following behavior [2], traffic microscopic simulation models now
23 include multiple detailed behaviors and have reached a high level of maturity not only among the research
24 community but also at the practitioners regular [1]. For a comprehensive review on all driving behavior
25 components used in simulation, the reader should refer to [1], [3].

26 Commercial simulation tools have devoted a large share of their new features to enhanced interfaces,
27 visualizations and, sometimes, calibration frameworks. At the same time, they have managed to integrate
28 dedicated traffic control modules, public transportation and pedestrian simulation [4], [5], into their core
29 architecture. On the other hand, the simulation research stream has proposed several innovative driving
30 behavior models [11],[24] integration of communication technologies or even emissions models [20]. Some
31 of these features can also be found in case studies using commercial software, but typically by means of
32 coupling external modules to the main simulation tool, eventually compromising computational
33 performance and interactive behaviors. Furthermore, several recent efforts in the research community can
34 be found in the development of sophisticated activity-based modelling frameworks and their integration in
35 simulation platforms that focus on individual’s entire day activity pattern. Comprehensive agent-based
36 modelling structures developed so far can be listed as TRANSIMS [17], MATSim [18] and FEATHERS
37 [19]. These applications model the multiple choices and behaviors of a single agent during a day and have
38 shown to better represent the interactions and dependencies of individual mobility. However, computational
39 efficiency of such platforms are always been a major concern as they usually deal with the entire population
40 of an area which is synthetically generated.

41 The above development streams have raised several challenges in the integration of complex
42 mobility and transportation models within microscopic simulation. The next generation of simulators
43 should include activity-based frameworks, integrated formulations with higher level, consideration of
44 alternative modes such as on-demand mobility and autonomous vehicles, advanced and flexible driving
45 behavior models, the possibility to easily integrate innovative transportation services such as vehicle-to-
46 vehicle communication or logistic services.

47 This paper presents SimMobility Short-term (SimMobilityST), a new open-source microscopic
48 mobility simulator integrated in a multilevel simulation platform. Designed using an agent-based
49 framework, SimMobilityST aims at simulating the movement of agents (traffic, transit, pedestrians and
50 goods) and the decisions and operation of control centers, within one day. It considers individual travel

1 behavior in detail using an activity-based formulation. In the next two sections both the modelling
2 framework and the system architecture are presented. Its modular structure is described in more detail with
3 a focus its multiple components along with the recent applications that showcase its flexibility in the
4 simulation of different and innovative mobility scenarios. Finally, the successful calibration process of the
5 demand-supply parameters of SimMobilityST for the city of Singapore is described.
6

7 **2 SIMMOBILITY**

8 **2.1. Overall Framework**

9 SimMobility is designed as three primary modules segmented according to timeframes [27]. The
10 short-term model functions at the operational level; it simulates movement of agents at a microscopic
11 granularity (within day) and is presented in more detail in the next section. The mid-term (day-to-day)
12 simulator handles transportation demand for passengers and goods; it simulates agents' behavior including
13 their activity and travel patterns; and it shares several mobility decisions with the short-term level (e.g.,
14 with the route-choice model) [38]. The long-term (year-to-year) model captures land-use and economic
15 activity, with special emphasis on accessibility. It predicts the evolution of land use and property
16 development and use, determines the associated life cycle decisions of agents, and accounts for interactions
17 among individuals and firms. The high-level design of SimMobility is shown in **FIGURE 1**.

18 SimMobility must therefore include all the key mobility-related decisions that people make in their
19 everyday life. These decisions may be personal decisions of households or the commercial decisions of
20 firms [26]. To support this level of representation, SimMobility is based on the concept of agent-based or
21 micro-simulation. Representation of individuals as agents in the model is necessary to simulate how people
22 will react in the future to new infrastructures, new technologies, innovations in system management and
23 policy changes.

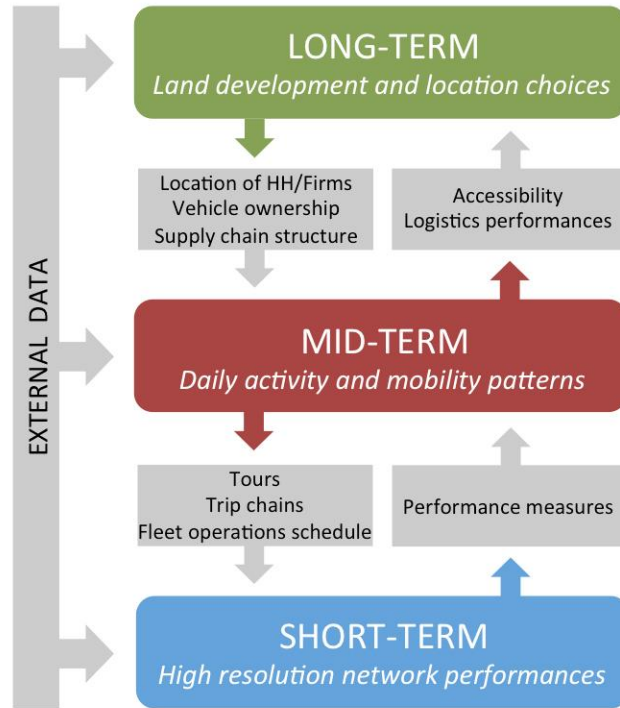
24 The SimMobility framework is fully modular in the sense that each of the levels can run
25 independently and only access the other levels when necessary. The key to multi-scale integration in
26 SimMobility is a single database model that is shared across all levels. Every agent exists and is recognized
27 at all levels simultaneously, and information is used according to each level's needs; in this way, behaviors
28 will remain consistent and, even if run separately, the impacts from one level's model will be propagated to
29 the others gracefully.

30 In previous work, these models have not been fully integrated. While there is limited interaction of
31 outputs, there is no internal coherence. SimMobility is unique in that the same pool of agents is used across
32 all timeframes. For further details on SimMobility's overall framework and Mid-Term and Long-Term
33 Simulators, the reader is referred to [27],[38] and, [50] respectively.
34

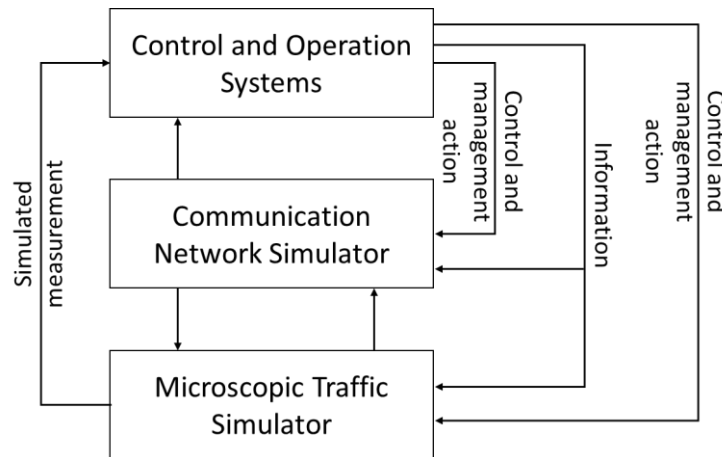
35 **2.2. SimMobility Short-term Framework**

36 SimMobilityST is an agent-based, multimodal microscopic simulator where agents' movements are
37 captured at a very fine resolution (up to 100 milliseconds). SimMobilityST comprises three main
38 components. The Microscopic Movement module is responsible for advancing drivers, pedestrians and
39 goods on the transportation network according to their respective behavioral and decision models. The
40 Control and Management module simulates the control centers, such as traffic and parking control, bus
41 control, rail control, autonomous fleet control, logistic control, etc. The outcomes of these control actions
42 will influence an agent's movement decisions, path choices and other related decisions in the movement
43 simulator. Within the Control and Management Module, different control centers may be considered and
44 replicated. At the current state of the simulator, the service controller and the traffic management controller
45 are operational as described below. On-going efforts are being made in the development of the freight
46 controller using detailed freight and logistics data [47]. The third component is the Communication network

1 simulator, which simulates agent-to-agent communications. The information can be passed from one agent
 2 to another via the mobile communication or via vehicle-to-vehicle communication or maybe via vehicle-
 3 to-infrastructure communication. The Communication network simulator is responsible for simulating the
 4 physical communication network (for example, a wireless network), and agents simulated within
 5 microscopic traffic network will use this simulated network to pass information between them. This will
 6 help the agents to get the realistic communication network, which will handle the message delivery delay
 7 or coverage.
 8



(a) High-level SimMobility Framework



(b) Short-term Framework

FIGURE 1 Framework of SimMobility and SimMobility ST

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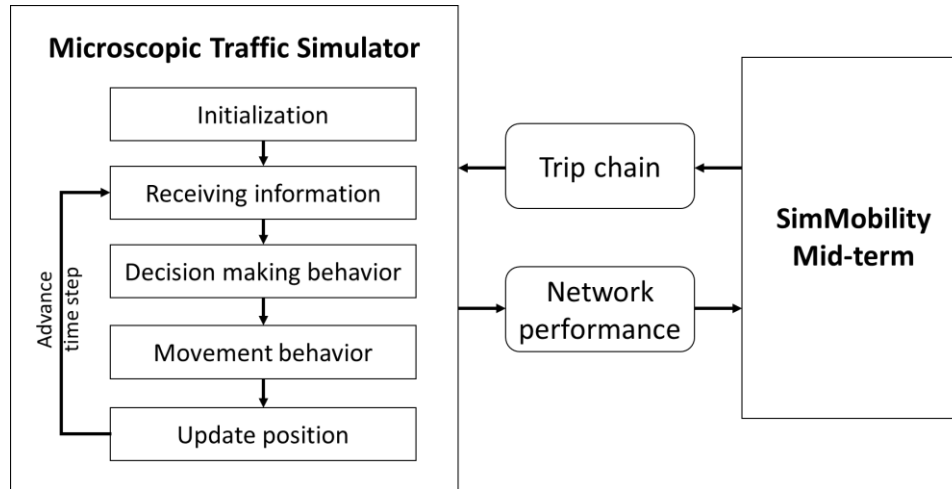
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1 3 MODULES

2 3.1 The Microscopic Traffic Simulator

3 The structure of the Microscopic Movement module is detailed in **FIGURE 2**. The virtual world is
 4 populated during the initialization phase, after which the simulation receives the control information/action
 5 plan at every time step. Two kinds of behaviors are simulated: high level (travel) decisions, such as route
 6 choices, are taken at some decision point (e.g., a bus stop). Lower level or movement decisions, such as car
 7 following and lane changing, occur while the agent is in movement. While the agent's position is updated
 8 at every time step, the movement-related decisions only takes place when specific events occur.
 9



10 **FIGURE 2** SimMobility Short Term Simulator

11 Demand input

12 Instead of the traditional Origin-Destination matrix definition used in the demand formulation of
 13 traffic microscopic simulation models, SimMobilityST (and its higher level counterparts) uses an activity-
 14 based demand formulation in the form of activity-schedules. In such approach, trip chains are generated by
 15 individual daily schedules instead of aggregated traffic specific matrices. Such data can be obtained directly
 16 using mobility and goods survey data or using a pre-day model, such as the one integrated in the
 17 SimMobility mid-term framework [38]. The pre-day model consists of an activity-based modelling system
 18 formulated as interconnected discrete choice models representing choices at distinct dimensions. This pre-
 19 day model development follows the Day Activity Schedule approach [25], [26] which focuses decisions
 20 related to daily activity and mobility. There are three different hierarchies in the system: day pattern level,
 21 tour level and intermediate stop level. Each level consists of several models, such as mode choice or
 22 departure tie choice. For the full specification of the pre-day in SimMobility Mid-term model, the reader is
 23 referred to [27]. The output is an activity schedule and the trip chains for each agent in the simulation.

24 Within SimMobilityST, agents are then moved as per the planned trip chain. However, the realized
 25 trips can be changed during the simulation if specific circumstances such as high congestion, incidents,
 26 public transportation interruptions or any control or information provision are observed.

27 For each agent's sub-trip (a multimodal trip can have several sub-trips) generated in the simulation
 28 its role is assigned (pedestrian, passenger and driver) and its role-specific characteristics are generated (e.g.,
 29 aggressiveness, look-ahead distance, reaction times, etc). For each vehicle-based trip, an individual vehicle
 30 is generated. On-going work is being carried out to allow vehicle ownership and parking models to integrate
 31 a consistent vehicle generation model with unique identifiers. The generated vehicles are then assigned
 32 vehicle attributes (e.g., type and drive train) based on configurable distributions.

1 **Static Supply input**

2 The network in SimMobilityST is composed by a road network layer, a pedestrian network layer
3 and a public transportation layer. The road network layer is composed by (1) Nodes, (2) Links, with (3)
4 Segments, (4) Polylines, and (5) Lanes. Connectivity attributes is assured by (6) Lane Connectors, (7)
5 Turning Groups, (8) Turning Paths and (9) Conflict Points.

6 Nodes represent intersections or source/sink for trip chains. They are used for Link definition in
7 route-choice and for the detailed characterization of intersections. Links are directional roads that connect
8 Nodes and are composed by Segments. The latter are road sections with uniform geometric characteristics
9 (speed limit, design speed, grade). Each segment as a fixed number of Lanes, each with its specific lane
10 rules (lane changing regulation and use privilege). Polylines determine the shape of the Segment and lane
11 connectors define the connectivity between Segments. At the Node level, Turning Groups, Turning Paths
12 and Conflict Points can be defined. Turning groups define the connectivity between Links, while the
13 Turning Paths Additionally, (10) Road Items are point specific features that can be added to the network to
14 represent items on the road to which drivers must respond (e.g.: traffic lights, bus stops, etc). On-going
15 work is being carried out to extend this framework with parking infrastructure.

16 **Driving behavior**

17 The core traffic model of SimMobilityST is based on MITSIM, an open-source microscopic traffic
18 simulation application developed by the Massachusetts Institute of Technology. MITSIM moves vehicles
19 according to route choice, acceleration and lane changing models. The acceleration model captures drivers'
20 response to neighboring conditions as a function of surrounding vehicles motion parameters. The lane-
21 changing model integrates mandatory and discretionary lane-changes in single model. Merging, drivers'
22 responses to traffic signals, speed limits, incidents, and tollbooths are also captured. The driving behavior
23 models implemented in MITSIM are those estimated by [22] and [21]. The MITSIM lane-changing model
24 was later enhanced by [24], for the specific purpose of integrating latent plans in the lane selection process,
25 namely in urban arterials and in freeways with a large number of lanes.

26 Several additional enhancements were made to the MITSIM original driving behavior: an enhanced
27 reaction time formulation capable of explicitly model reaction time and perception delays for each person
28 in a detailed and flexible manner as introduced (see [28] for further details); lateral movement during lane-
29 change was also included. For the current implementation, the lateral speed is kept constant during the lane-
30 change, but the implementation of a sine function for lateral acceleration similar to the one proposed in
31 [30] has been initiated.

32 Finally, the design of a dedicated intersection behavior model, based on the conflicts technique has
33 also been implemented. The intersection behavior starts once the intersection is visible to the vehicle. First,
34 the driver identifies the intersection regime (no rules, priority, or controlled). If the intersection is not
35 controlled, the subject vehicle identifies the neighboring vehicles and the conflicting vehicles, and proceeds
36 with a gap-acceptance based model that accounts for intersection-specific priorities (if any).

37 **Travel behavior**

38 Within SimMobilityST, changes in planned trip chains have to be considered. As the simulation is
39 running, the agents need to find the routes for their trips and transform the activity schedule into effective
40 decisions and execution plans. Agents may get involved in a multitude of decisions, not constrained to the
41 planned set of destination, mode, path and departure time depending upon the network and their state in the
42 simulation cycle [38]. In the current implementation agents can re-route (as drivers or public transportation
43 passenger) in the presence of congestion or the provision of control and information. Route choices are
44 based on a probabilistic model that captures the impact of travel times and biases toward routes that use
45 freeways over urban streets. The impact of real-time information on routing decisions is captured by a route-
46 switching model in which informed drivers re-evaluate their pre-trip route choices based on the traffic
47 conditions observed en-route. For perfect model integration with higher level simulators, the route-choice

1 model used in SimMobility ST is the same as the one used in the SimMobility Mid-Term framework and
2 can its details be found [38], [27].

3 **Pedestrian movements**

4 The pedestrian behavior model focuses on the problem of how a pedestrian makes crossing-related
5 decisions at different levels and at different points of times, when she/he walks along a given path to
6 destination. Specifically, a crossing choice module is designed to determine where a pedestrian crosses the
7 road, along a given path. A crossing timing decision module is designed to control when a pedestrian starts
8 crossing the road, once she/he reaches a crossing point. At the time of writing this paper, pedestrian's
9 microscopic movement has been implemented in a simplified way with constant speed and unified crossing
10 time synchronized with pedestrian traffic light change.

11 **Commodity movements**

12 The movement of freight vehicles is typically considered in microscopic traffic simulation models by means
13 of adapting driving behavior parameters for heavy vehicles [31] or by coupling dedicated external
14 applications with the simulator [32]. Teo et al. [33] extended these traditional approaches by integrating the
15 simulation of freight movements, logistics decisions and traffic within an agent-based simulation.
16 SimMobilityST is the first microscopic simulator that integrates commodity specific movements with
17 detailed traffic models. Similarly to individual trip-chain input, SimMobilityST allows commodity specific
18 shipments. The commodity entity was specified for this purpose and freight drivers are assigned tours based
19 on the commodities to deliver during the simulation period. A default tour generation model was developed
20 but this will be relaxed and linked to a freight operator controller, which typically represents a carrier.
21 Freight vehicles and drivers will then be assigned to a specific freight operator and a set of delivery stops
22 specified as Road Items in the network. Decisions on the freight vehicle tours can be made by the freight
23 operator controller or the driver himself. The design and integration of all these entities within the core
24 models of SimMobilityST is still under development at the stage of writing this document.

25 **3.2 Control and Operation Systems**

26 **Traffic Management Controller**

27 The Traffic Management Controller mimics the traffic and information control system in the
28 network under consideration. A wide range of traffic control and route guidance systems can be simulated.
29 These include intersection controls, ramp control, freeway mainline control, lane control signs, variable
30 speed limit signs, portal signals, variable message signs and in-vehicle route guidance. The Traffic
31 Management Controller can represent different designs of such systems with logic at varying levels of
32 sophistication (pre-timed, actuated or adaptive) by means of a flexible configuration input.

33 Control devices can be either link-wide (such as Variable Speed Limits) or lane specific (e.g.; lane
34 use regulation). They are represented by Road Items and are characterized by their location, type and
35 visibility distance. Their logic is implemented directly by the Traffic Management Controller and the
36 analyst will need to code its logic through external scripting files (in Lua language). An example of tested
37 implementation in the current state of SimMobilityST development is the SCATS-like algorithm for traffic
38 signals [29] and an innovative time slot-based algorithm for the coordinated management of intersections
39 for autonomous vehicles [45].

40 **Service Controllers**

41 Service controllers are the central control point responsible for operation a specific mobility
42 service. It holds relies on static information (e.g.: vehicle fleet composition, routes, etc) as well as real time
43 information (e.g. traffic sensor measurement of vehicle location data) and communicates with the simulated

1 vehicle operators/drivers to send them instruction at various situations. In the current development of
 2 SimMobilityST, the bus transportation framework and controller are already implemented. We currently
 3 have two setting of the controller: the Bus Controller and the Smart Mobility Controller.

4 The Bus Controller is responsible for the scheduling and dispatching of buses, for keeping track of
 5 individual arrival times, and for deciding on transit control strategy. Along with the Bus controller, other
 6 features were implemented in SimMobilityST: the Bus Driver Agent will be responsible for routing the bus
 7 on fixed route, the bus movement near the bus stop, real time passenger count and dwell time calculation.
 8 The bus movement for example, includes mandatory lane-changing maneuvers in order to reach the lane
 9 where the stop is, depending on a distance-to-stop threshold. When a bus is far than bus-to-stop visibility
 10 the driver agent may make discretionary lane changes according to the same logic that applies to other
 11 drivers with a preference toward the lane that contains the bus stops; finally, the Passenger/Pedestrian
 12 Agents will also interact in the bus framework as they are responsible for realizing their individual bus
 13 route choice, boarding choice and alighting choice.

14 To provide reliable service the bus controller may implement different strategies, and holding
 15 strategy is one of them. Different holding strategies have already been implemented and tested in
 16 SimMobilityST: schedule-based, headway-based and even headway-based strategies.

17 SimmobilityST also provides mechanisms for simulating emerging technologies that are yet to be
 18 widely available, for example, mobility-on-demand services. Such feature was achieved with the
 19 development of uniform interfaces between a Smart Mobility Controllers and the different models in
 20 SimMobilityST. The Smart Mobility Controller relies on third-party code that can run separately from
 21 SimMobilityST and mimics the operation of fleets, from regular taxi to Uber-like systems. This code
 22 interacts with agents and entities in SimMobility in runtime, and a few features have been made accessible
 23 to it.

24 Two application of the proposed Smart Mobility Controller can be found already in the literature:
 25 an Autonomous Mobility on Demand (AMOD) service, which provides one-way car-sharing with self-
 26 driving electric vehicles and has emerged as a promising solution for autonomous urban transportation [48];
 27 and Flexible Mobility on Demand (FMOD), which provides personalized and optimized services to
 28 travelers in real-time with flexibilities both on the operator and traveler side [49]. These technologies are
 29 designed to deal with the recent trends that emphasize more flexibility through the use of shared-ride
 30 services and integration of multimodal mobility options.

32 **3.3 The Communication Network Simulator**

33 Many simulators broaden their applicability by allowing customized interactions with third-party
 34 components, and SimMobility is no exception. In addition to traditional library-based extension,
 35 SimMobilityST provides a TCP socket integration layer that allows other software systems to interact with
 36 a running SimMobilityST simulation. This is primarily used in [34] to overlay Android emulators running
 37 transit-related applications or “apps” onto existing SimMobility agents, thus providing accurate location
 38 information to the apps. In return, the apps provide more realistic within-day re-routing, creating a feedback
 39 loop which should optimize the system.

40 The choice to communicate over TCP sockets has several advantages. First, it requires minimal
 41 changes to existing third-party software systems –usually only a small communication module is needed.
 42 Second, it facilitates interactions between a larger number of simulators. In the example just discussed,
 43 SimMobilityST connects to a running instance of a network simulator (ns-3), which it uses to provide
 44 accurate timing and packet loss information for messages sent between Android clients. Finally, the use of
 45 TCP sockets provides a stable, cross-platform means of interaction with clearly defined boundaries.

47 **4 SYSTEM ARCHITECTURE**

48 **4.1 Overall framework**

49 SimMobilityST applies several design heuristics to make modelling and development easier for a

1 heterogeneous user base. First, entities are isolated from each other, and can only interact through properties
 2 that are shared among them. This isolation is achieved through the use of agent-based simulation
 3 techniques. Second, the simulator is location-agnostic regarding agents. In other words, an agent's interface
 4 does not change depending on where it is in relation to other networks (except when MPI is enabled). Third,
 5 SimMobilityST's time-step is indivisible –agents are assumed to all tick forward at once. Finally,
 6 SimMobility is hierarchical and provides sensible defaults. A good example of this behavior is the use of
 7 trip-chains, which can be “filled in” with more information as the agent's trip progresses. If an agent does
 8 not have a route for a given segment of the trip chain, one can be estimated for it.

9 SimMobilityST is designed as a hybrid software framework, including both event-driven
 10 messaging and discrete time-step simulation. Heterogeneous time-steps are supported, allowing coarse-
 11 grained software agents such as traffic signals to interact efficiently with fine-grained agents like drivers.
 12 Ultimately, SimMobilityST was designed with accuracy and performance as its two primary goals. To this
 13 end, it includes a parallel and a distributed component, which will now be described in turn.
 14

15 **4.2 Parallel computing**

16 SimMobilityST features a robust, straightforward approach to massive parallel scalability that was
 17 designed to take advantage of the processing power of modern hardware. The majority of computations
 18 performed by SimMobilityST are done by entities as they update their internal state. This process is
 19 performed once per entity per time tick. Entities with similar time step resolutions are grouped together into
 20 Workers that manage the update process for a given thread.

21 Entities can generally ignore the Worker that they assigned to, as all communication through other
 22 agents is done using buffer-backed variables. These variables use an internal buffer to allow lock-less
 23 communication with any entity on any Worker. In addition, Entities will be automatically added to a Worker
 24 when their start time of their first trip arrives, and will be removed once the final trip's destination has been
 25 reached. Typically, entities only interact with their Workers when requesting a manual migration. This can
 26 occur when the agent crosses an MPI boundary (described in Section 4.3), or if some kind of spatial
 27 optimization such as the mid-term's “conflux” structure is desired.

28 This use of buffers runs counter to traditional logic of using mutex-based locking for parallel
 29 communication. Ultimately, the conventional approach exhibits several systemic and non-trivial problems.
 30 Primarily, it limits the repeatability of the simulation by introducing an unacceptable amount of non-
 31 determinism. Entities are constantly reading and reacting to the internal state of each other, and performing
 32 these reads in parallel leads to different orderings for each simulation run. Attempting to solve this by
 33 ordering entity updates will remove some of the benefits of parallelism, which is particularly detrimental
 34 to entities that are not sensitive to update order. A secondary issue with lock-based synchronization is the
 35 heavy toll it places on many-cored systems, especially in traffic simulation with its high degree of inter-
 36 agent data dependency. As the number of discrete processing units on a system increases, more and more
 37 performance is lost to overhead.

38 An additional channel for communication is event-driven messaging. Here, entities can register for
 39 messages to be delivered for a series of given events, such as node arrivals or agent deactivations. These
 40 messages will be triggered during a time tick, gathered and sent at the end of that time tick, and received at
 41 the beginning of the next time tick. Thus, messages inherently incur a one-tick delay, although it is possible
 42 to reduce this to zero if certain conditions hold (e.g., passengers on a bus can receive zero-delay messages).
 43 Although event processing is inherently single-threaded, it can lead to large performance gains by allowing
 44 entities to deactivate their update phase until a given message arrives. Furthermore, entities can register for
 45 events and still maintain their update phase, thus allowing for a hybrid of event-driven and discrete time-
 46 stepped simulation.
 47

48 **4.3 Distributed computing**

49 Once simulations encompass a large enough number of entities, it is inevitable that parallel

1 simulation will reach a point of diminishing returns. At this point, the simulation must be split and run on
2 different machines (“nodes”) through SimMobilityST’s MPI-based distributed computing platform.
3 Although the same parallel setup just discussed is still run on each node, the inter-node communication is
4 inherently less flexible and requires modelers to abandon the location-agnostic property of the single-node
5 setup. In particular, entities must be located in a particular geometric “space”, and various spatial
6 decomposition techniques are used to assign different spaces to different physical machines. The
7 implications of this will now be discussed.

8 The global state of the simulation, including the road network and the trip chains, is split and
9 distributed to each node, whereupon it is loaded on an as-needed basis (to reduce memory usage). Agents
10 are distributed to the node which contains their starting trip, and will be automatically transferred to other
11 nodes as they cross the relevant node's boundary. A node boundary is defined as a line perpendicular to a
12 given road segment which divides the upstream and downstream halves of that segment between two nodes.

13 Entities on different nodes can sense each other via mirroring, but they cannot otherwise interact.
14 Furthermore, entities that are not in a mirrored region cannot send each other messages unless they are on
15 the same node. This is an unfortunate necessity, as it puts a lower bound on the number of nodes that a
16 given node must interact with, in turn allowing SimMobilityST to scale efficiently up to arbitrarily complex
17 road networks and simulation workloads. In order to work around these limitations, a delayed-hopping
18 message protocol is in development which allows messages to be sent to agents on other nodes at a time
19 cost of N time ticks, where N is the number of nodes between the originating agent and the receiving agent.
20 This system is flexible, and permits the time delay to be further reduced (to at least 1) through the use of
21 software-defined relays.
22

23 **4.4 Visualizer**

24 To represent the simulator output graphically an interface is developed in C++ using QT libraries.
25 This GUI is used for debugging purpose and to demonstrate of traffic impact through vehicle animation
26 (**FIGURE 3**). This application accepts the simulator output file produced in plain text format and then it
27 display’s vehicle trajectory at each frame tick and also saves the simulator output in the database for efficient
28 subsequent runs. It supports zoom-in and zoom-out operation handle large or small area visualization, road
29 network entity search functionality to locate object easily within the GUI. It also provides user to edit the
30 road network and convert them in SimMobility XML format. The Visualizer is capable to read large
31 simulator output file and more optimization techniques are in progress to make it more efficient.
32

33 **4.5 Data management**

34 SimMobilityST supports multiple data interfaces to exchange data with the other level or the data
35 those are exogenous to the simulator. It is able to read or write data from/to XML files, PostgreSQL database
36 and the CSV files. This will give user greater flexibility to run SimMobilityST with variety of data sources
37 depending on the experiment requirement. SimMobilityST data requirement can be grouped into:
38 Configuration, In/Output data, Model parameters.

39 SimMobilityST stores the configuration data and the model parameters in XML format. It provides
40 greater readability for the user to configure SimMobilityST (see Section 6). Simulation input data can be
41 either exogenous to the system for example road network, traffic light phases etc. or received from other
42 level of SimMobilityST for example trip chains received from mid-term to short term. SimMobilityST
43 supports both XML and Database interfaces for input data and depending on the simulation need user can
44 specify the format in the configuration file. Usually if the simulation is required to run for a large area with
45 massive number of agents database is more appropriate option. Simulation outputs are generated in plain
46 text format that can be used for further processing and also the required portion is written in the database
47 for passing to the next level.
48

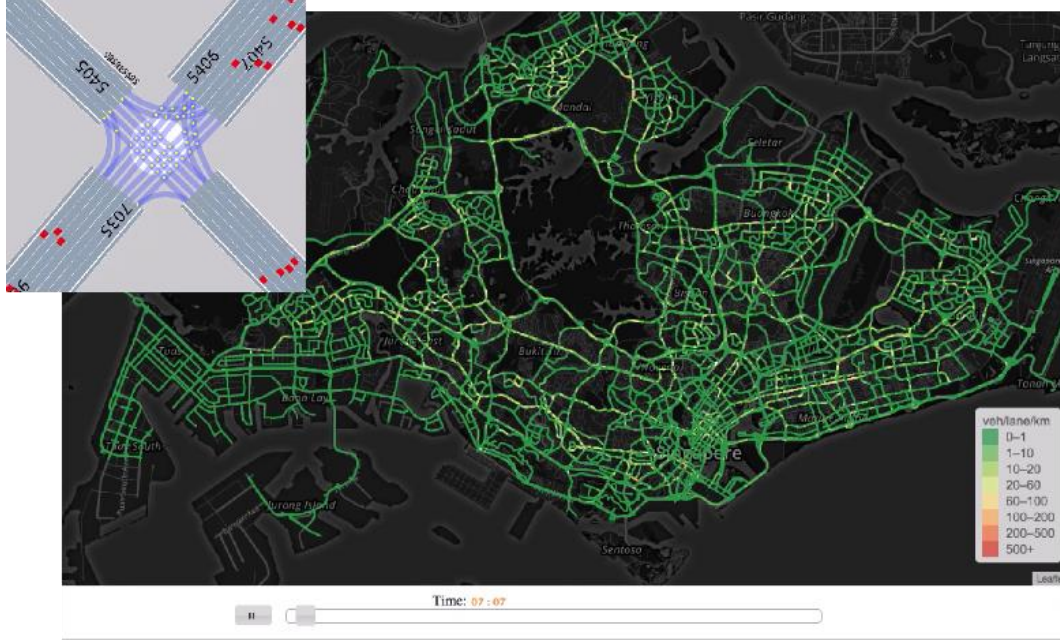


FIGURE 3 SimMobility Visualizer (Singapore simulation)

1

2 **5 CALIBRATION**

3 **5.1 Demand and supply parameters**

4 Demand parameters are typically calibrated through tuning of the OD flows. As SimMobility use
 5 activity schedules and trip chains instead of OD matrix, we aggregate the trip chain to generate OD
 6 parameter which to be calibrated, then, convert the updated OD parameter ($\hat{\theta}_{k+1}$) into trip chains by
 7 disaggregating through so-called ‘killing-cloning process’ for each iteration (k). Thus, each activity
 8 schedule will be “parameter” to be calibrated (killed or cloned). This means that each individual activity
 9 schedule, and therefore each agent, will be calibrated. Each activity schedule is considered as fixed, but
 10 replicates can be generated in the calibration process. The integrated calibration of Mid- and Short-Term
 11 simulators would relax this assumption by calibrating directly activity based model parameters as the
 12 demand.

13 Other parameters in demand side are route choice parameters. Route choice model for private
 14 transport corresponds to a Path-Size Logit Model [39]. Accordingly, drivers’ route choice decisions are
 15 captured in a probabilistic manner, and highly likely to choose the route that maximizes his/her utility which
 16 is characterized by influencing factors including travel-time and distance. On the supply side, all driving
 17 behavior parameters are considered [21], [40].

18

19 **5.2 Calibration framework**

20 The simultaneous calibration of demand and supply parameters generate a large set. To deal with
 21 such complexity, we used the Weighted Simultaneous Perturbation Stochastic Approximation, W-SPSA
 22 ([36], [37]). The algorithm finds the best parameter set by iteratively updating the parameter set to the
 23 decreasing direction in goodness-of-fit (GoF), which may reply on existing measurements and on prior
 24 knowledge on demand-supply parameters from previous experiments. Through the ‘killing-cloning
 25 process’, we run the SimMobilityST to get initial simulation output and assignment matrix. The assignment
 26 matrix as weight matrix for the measurements in W-SPSA. After initial setting, the calibration loop runs
 27 until reach to the convergence condition and objective value is within an acceptable level of performance.
 28 The optimization problem over parameter space during the period of $H = \{1, 2, \dots, H\}$ can be formulated

1 as:

$$\begin{aligned}
2 \quad & \min_{x, \beta} z(\theta) = \sum_{h=1}^H [w_C z_C(C_h^O, C_h^S) + w_p z_x(x_h, x_h^a)] + w_p z_\beta(\beta, \beta^a) + w_p z_\gamma(\gamma, \gamma^a) \quad (1) \\
3 \quad & \text{s.t. , } C_h^S = f_1(x_1, \dots, x_h; \beta; \gamma), \text{ lb}_{x_h} \leq x_h \leq \text{ub}_{x_h}, \text{ lb}_\beta \leq \beta \leq \text{ub}_\beta, \text{ lb}_\gamma \leq \gamma \leq \text{ub}_\gamma
\end{aligned}$$

4

5 where, z_C measures GoF between externally observed count (C_h^O) and simulated count (C_h^S); z_x
6 compares estimated time-dependent OD parameter (x_h) with the seed OD (x_h^a) from MT; z_β and z_γ
7 respectively evaluates the estimated parameter set in driving behavior (β) and route choice (γ) against a
8 priori values (β^a, γ^a); and θ is decision vector ($\theta = [x_1, \dots, x_h, \beta, \gamma]$). The parameters are bounded
9 upper/lower limits. Note that each evaluation term includes weighting coefficient ($w_C; w_T; w_p$), which
10 determined by the reliability on the external information.

11

12 W-SPSA selectively perturbs relevant parameters based on a weight matrix (w) which represents
13 spatiotemporal correlations between each parameter and measurements. Readers can refer the full structure
14 of W matrix from [43]. To increase applicability in ST calibration, which deals with large number of
15 agents for large spatial ranges, a sparse matrix has been generated in this phase. Then, the gradient
16 approximation can be formulated as:

$$16 \quad \hat{g}_{ki}(\hat{\theta}_k) = \frac{\sum_{j=1}^D w_{ji} [(\epsilon_{kj}^+)^2 - (\epsilon_{kj}^-)^2]}{2c_k \Delta_{ki}} \quad (2)$$

17

18 where, c_k, Δ_{ki} indicate the perturbation amplitude and random perturbation vector (following
19 Bernoulli process) respectively. Also, note that $(\epsilon_j^+)^2$ and $(\epsilon_j^-)^2$ represent deviation vectors measuring
20 distance between the observed and the simulated measurement with plus ($\hat{\theta}_k + c_k \Delta_k$) and minus perturbed
21 parameter ($\hat{\theta}_k - c_k \Delta_k$) respectively. \hat{g}_{ki} is the i^{th} element of the approximation of the gradient vector.
22 This gradient provides the amount of movement from current k^{th} state ($\hat{\theta}_k$) to the next iteration ($\hat{\theta}_{k+1}$).

23

Using Eq. 2, we update $\hat{\theta}_{k+1}$ which yields less cost on evaluation function:

$$23 \quad \hat{\theta}_{k+1} = \arg. \min_{\hat{\theta}_{k+1}} \left(z(\hat{\theta}_{k+1} = \hat{\theta}_k - \alpha_k \hat{g}_k(\hat{\theta}_k)), z(\hat{\theta}_{k+1} = \hat{\theta}_k + \alpha_k \hat{g}_k(\hat{\theta}_k)) \right) \quad (3)$$

24

25 where, α_k is a step size in a gain sequence. Therefore, SimMobilityST calibration includes a
26 backward decision process that gives additional chance to consider opposite direction in the decision vector
27 update. Also, note that the two different function evaluation on two parts (Eq. 2) conducted on a parallelized
28 way its independent each other and the algorithmic parameters are selected as in [41]. Once objective value
29 satisfies the internal convergence term, we terminate full calibration process.

30

30 5.3 Experimental setting

31

32 SimMobilityST is calibrated by running the traffic for the extended Central Business District
33 (CBD) in Singapore (FIGURE 4). This area contains more than 1200 intersections, which covered by more
34 than 2000 loop detectors. A smaller sub-network called Bugis, located inside CBD (10 intersections), was
35 also tested for assessing the impact of daily variability in the calibration process. The aggregated demand
36 generated by SimMobility MT has 1497 observed ODs pairs and a total of 48,988 trips. These trips
37 (demand), 11 route-choice parameters for demand and 112 driving behavior parameters (supply) are the set
38 of parameters to calibrate.

38

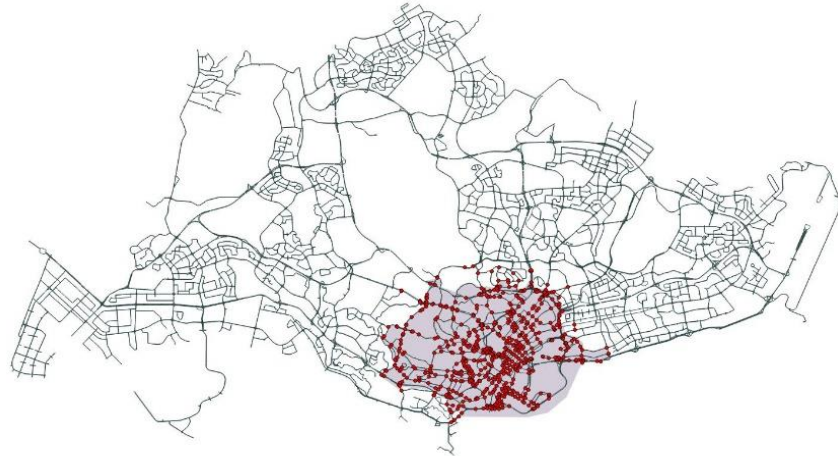


FIGURE 4 Extended Central Business District (CBD) in Singapore (shaded area; red dots are measurement locations)

For the calibration, two types of data were available: loop count and GPS travel-time data from probe vehicles, collected in August 2013 by the Land Transport Authority of Singapore and Taxi data location respectively. Counts had a resolution of 5min while the GPS data was structured in OD a travel-time tables for each 30min interval of the day. Counts were also preprocessed for outlier detection [44]. A total of 360 sensors were used in the calibration. The following data was also used in network settings: SCATS signal phases, GIS network configuration, Google transit network data for the buses routes and schedules, as well as freight (background) traffic data.

5.4 Calibration result

The result shows the calculated RMSN between the simulated and observed count over all segments and time intervals. **TABLE 1** shows RMSN for multiple days in small Bugis network. This shows that the calibration framework is able to calibrate simulator using different external data sets, with improvements 40~50% in RMSN. In the extended CBD area and after 250 iterations, the fit-to-counts has been improved from 0.72 to 0.37 of RMSN (**FIGURE 5** (a)) and the calibrated counts became close to the 45-degree line (**FIGURE 5** (b)). The calibrated RMSN seems to be satisfactory given the above small number of sensors and relatively large number of parameters.

TABLE 1 RMSN for multiple days in Bugis network

Date in Aug./2013	6 th	7 th	13 th	14 th	15 th	20 th	21 st	22 nd
Initial	0.58	0.53	0.53	0.54	0.49	0.47	0.51	0.46
Calibrated	0.29	0.29	0.32	0.26	0.25	0.29	0.27	0.25

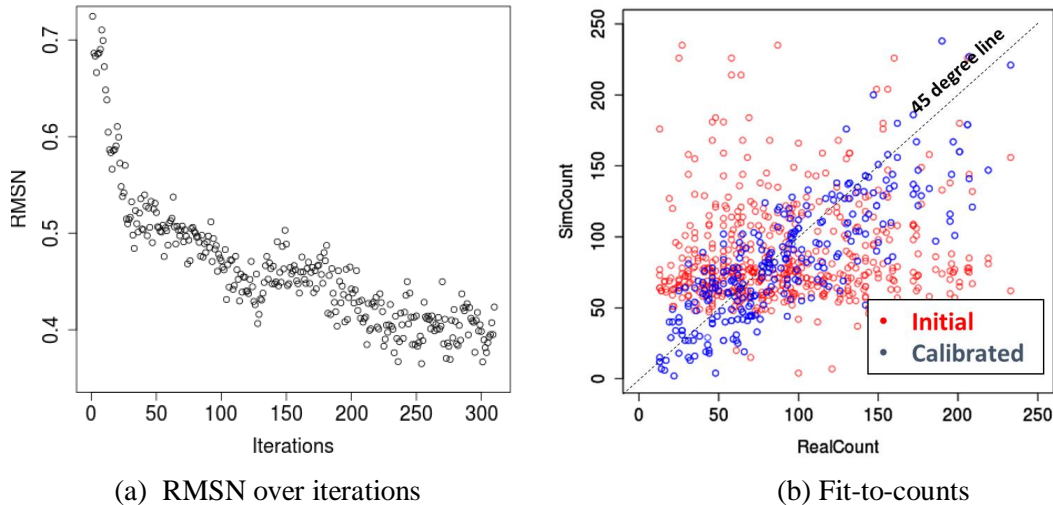


FIGURE 5 Calibration result for the Singapore extended CBD area

6 CONCLUSIONS

A microscopic mobility simulator, SimMobilityST, aiming at simulating the movement of agents (traffic, transit, pedestrians and goods) and the decisions and operation of control and logistic centers is presented. SimMobilityST allows for a modular integration of specific behaviors associated with new mobility services and transportation modes. It is integrated within the SimMobility framework, a multi-scale simulation platform that considers land-use, transportation and communication interactions using various behavioral models. The new simulator particularly focuses on impacts of innovative transportation services on transportation and mobility networks, thereby enabling the simulation of a portfolio of technology, policy and investment options under alternative future scenarios. SimMobilityST has been successfully calibrated using external data in Singapore. Multiple days supports the replicability of calibration capability as well. This calibrated simulator would contribute to increase simulation reliability in evaluation of new scenarios in Singapore and elsewhere.

The main on-going development efforts have been focusing in integrating further (existing) advanced driving behavior models; designing and implementing the urban freight tour-based logic, along with its specific behaviors and logistic decisions; and implement further smart mobility services.

Finally, the integration of a dedicated framework for simulating electrical vehicles and both environmental and safety impacts assessment modules are also three short-term key milestones. The first, will allow SimMobilityST to be used in the decision process of the design of the electrical vehicles grid and to model the associated changes in the mobility patterns at the city level. The environmental and safety impacts assessment modules will allow a more comprehensive evaluation of the technologies and services being tested within SimMobility.

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