Large-scale agent-based transport demand model for Singapore

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1 Introduction

1.1 Context and Motivation

This century will, for the first time, see over half the world's population living in cities UN (2007). Making these urban structures environmentally, economically and socially sustainable and liveable is one of today's great challenges. Due to its central importance of cities' infrastructure and performance, one key element to meet this challenge is transportation. Embedded in the Singapore National Research Foundation's initiative Campus for Excellence and Technological Enterprise CREATE, one project of the Future Cities Laboratory approaches the challenges of urban transportation planning that stem from managing, planning and optimising the flow of people and goods at different time scales and in its interaction with all elements of the future city. The basis of the research framework is a full implementation of the open-source multi-agent-based travel demand simulation MATSim [1] for the case of Singapore. The combination of a variety of advanced transport demand policies such as time dependent road pricing, a multi-modal public transport system and the dynamic further development of transport infrastructure makes Singapore arguably one of the most interesting places for an implementation of agent based transport demand model.

Open-source MATSim is one of a group of agent-based models that have recently been developed to realise the potential of the activity-based approach into practise Bradley and Bowman (2006). In line with the activity-based approach (Jones *et al.*, 1983), MATSim is based on the idea of the 24h daily activity schedule as the basic behavioural unit. In contrast to all other current agent-based models, except TRANSIMS Beckmann *et al.* (2007), MATSim employs fully integrated traffic flow simulations for both private and public transport including dynamic road pricing to calculate the generalised costs of travel implied by the schedule. In addition, MATSim is designed for speed and scale, which allows it to address large-scale and finely detailed scenarios, for example, Switzerland which has 7.5 million agents, 1.0 million links and 1.0 million destinations, and, to find a steady state solution with acceptable computing efforts (Balmer *et al.* (2010), Meister *et al.* (2009)), Toronto (Gao *et al.*, 2010), Berlin (Rieser *et al.*, 2008) or Tel-Aviv (Bekhor *et al.*, 2011).

1.2 Objectives

This paper presents the development of a large-scale the agent-based transport model for Singapore using MATSim. Earlier papers on MATSim implementations have focused on software architecture and simulation times (Balmer *et al.*, 2010) and conversion of an existing

[1] See `http://www.matsim.org`

transport demand model to MATSim (Bekhor *et al.*, 2011). In this paper, the design of the demand modeling process including all necessary sub-models, its sequence and thorough validation is central. Special attention is paid on the additional sub-models, which became necessary due to restricted availability of key data needed for agent-based transport demand modeling.

2 General Framework

2.1 Activity based transport demand modeling

The general aim of multi-agent simulation is a to integrate activity-based demand generation with dynamic traffic assignment. Activity-based demand generation models generate a sequential list of activities and trips connecting these activities for every person in the study area. Demand generation is embedded in a concept of daily activity demand from which the need for transport is derived (Kitamura, 1988). A major advantage of activity-based demand modeling is that both the spatial and temporal consistency of travel behavior can be ensured. For example, mode choice can be formulated on a subtour level, since the mode chosen for one trip may influence the mode choice for other trips of a given subtour (Ciari *et al.*, 2008). This is superior to traditional demand generation where aggregate traffic quantities represent isolated trips. Furthermore, not only temporal dynamics, but also temporal interdependency of activities and trips are inherently modeled. For example, a delay of scheduled activities caused by increased travel time due to congestion is propagated through the day and can either result in shortened or further postponed activities.

Several approaches a wide variety of methods have been developed to generate daily activity plans. On the one hand, random utility theory is used to generate daily activity plans. Examples are SACSIM for the Sacramento Area, California, and the comprehensive econometric microsimulator for daily activity-travel patterns (CEMDAP) applied to the Dallas-Fort Worth Area (Bradley *et al.*, 2010; Bhat *et al.*, 2004). On the other hand, in a rule-based approach demand generation is based on psychological decision rules observed in travel diary or stated-adaptation surveys. Examples include the travel activity scheduler for household agents (TASHA) for the Greater Toronto Area, and the learning-based simulation system ALBATROSS recently applied to the Netherlands in the context of an air-quality study (Roorda *et al.*, 2008; Beckx *et al.*, 2009).

Most of the above approaches to generate a regional transport model have in common that only the first three steps of the traditional four-step model are performed on the basis of individual travelers. For the traffic assignment step, the trips listed in the activity plans are independently aggregated to time-dependent (typically hourly) OD matrices which are fed into a dynamic traffic assignment (DTA) (Watling, 1996). Examples of DTA implementations are a dynamic version of VISUM (Vrtic and Axhausen, 2003), DynaMIT (Ben-Akiva *et al.*, 2002) and Dynasmart (Mahmassani *et al.*, 1992).

Conceptually, the iterative procedure of DTA can be extended to other dimensions of travel decisions beyond route choice. Examples are "best-reply" models for departure time choice (de Palma and Marchal, 2002; Ettema *et al.*, 2005) or optimal mode choice. Elements of demand generation are thus elevated from a simple pre-process to an integrated part of demand-supply equilibration, as mode choice, departure time choice or even the activity sequence may be susceptible to changes in traffic patterns.

One major constraint of the DTA based approach is that information on individuals can not be retained once demand is aggregated to matrices to compute flows. By introducing multi-agent transport simulation, this constraint is resolved and personal attributes such as sociodemographic properties, the activity plan, and other internal variables can be accessed during the entire modeling process. In such an approach, software objects representing travelers ("agents") are retained not only in the demand generation stage, but also in the assignment step (Rieser *et al.*, 2007).

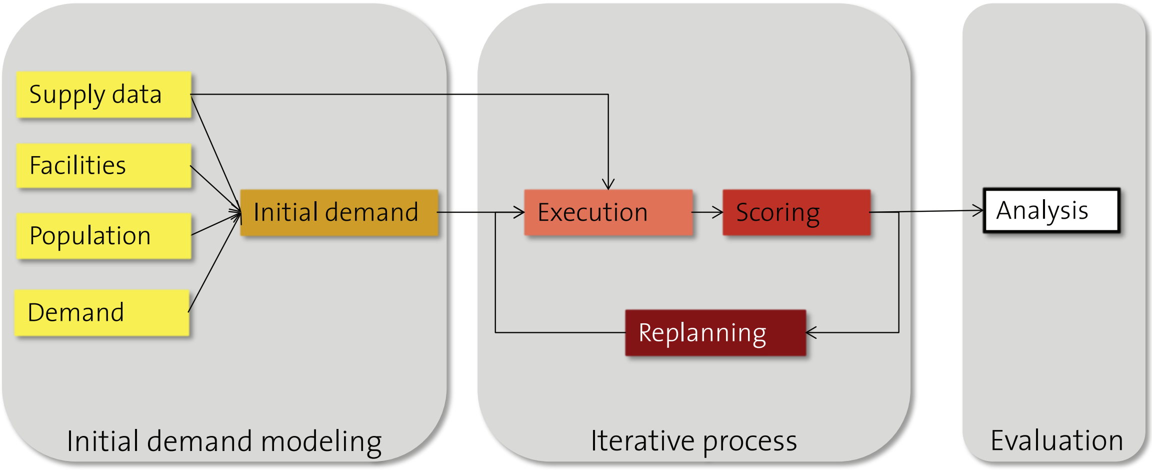
By including more dimensions of travel behavior, the repeated realisation of an activity based demand generation process become computationally more expensive. To resolve this issue, *learning* is introduced in the feedback cycle: An agent can hold a set of activity plans in its "memory", and chooses one of them for the traffic simulation (Raney and Nagel, 2006).

The open source MATSim (multi-agent transport simulation) is designed along those lines and allows the simulation of both private and public transport modes. The simulation structure of the underlying coevolutionary system is depicted in 1, and explained further in the following subsections. The initial demand generation results in daily activity plans which are composed of fixed and flexible elements. Whereas the activity chains (number, type and sequence) as well as the location of home, work and education activities remain unchanged during the whole process, start times and duration of activities, mode and route choice as well as activity locations for secondary activities, i.e. shopping and leisure are optimised in the iterative learning process until a relaxed state is reached.

2.2 Generating initial activity plans

The approach presented in this paper combines a variety of concepts used in earlier implementations of MATSim (e.g. Balmer *et al.* (2010), Balmer *et al.* (2009a) and applies it to the case of Singapore. Given the data availability in Singapore, additional submodels became necessary to achieve the project's goal of a full scale implementation of an agent-based transport demand

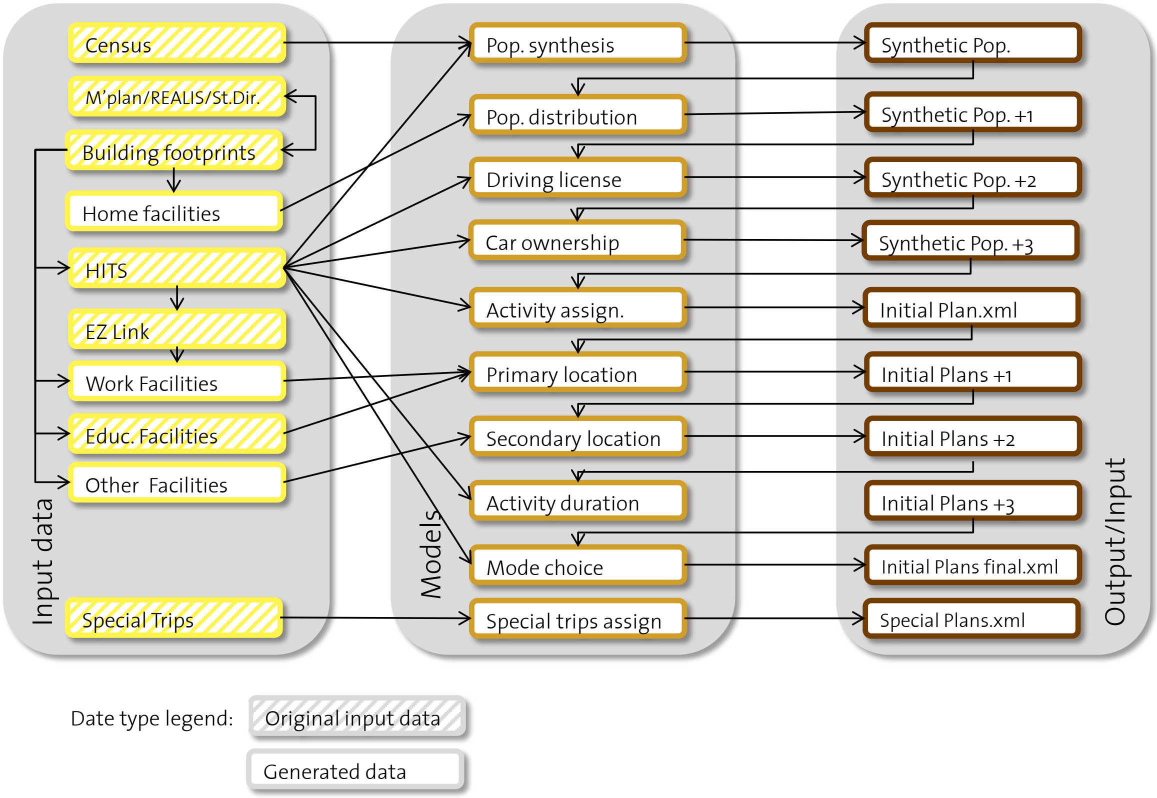
Figure 1: Structure of the MATSim-T simulation system



simulation featuring buildings as the base layer of spatial granularity.

The demand modeling process is illustrated in Figure 2. It combines diverse data on land use, travel demand, demographics and transport supply in order to generate initial daily activity plans. The sequential process starts with a populations synthesis. For each person in the study area, a synthetic "agent" is generated. While single persons do not necessarily need to be represented by a corresponding agent with the same socio-demographic attribute, the general statistical properties and correlation structure of the synthetic population should be representative for real population. Lacking a full census, for the case of Singapore an iterative proportional fitting approach on a household level was employed (see Section 3). The agent population is then spatially distributed taking into account the socio-demographic structure of the individual households based on a random sampling approach (see Section 4.2). To this end, a facilities data bases is established by combining information on building footprints, land use and diverse sources (see Section 4.1). Based on results of multinominal logit models that draw on information of the Household Interview Travel Survey (CITE), the synthetic population is enriched by availability of driving licenses on an agent's level and car ownership on a household level (see 4.2. Reported activity chains and preferred activity durations in the Household Interview Travel Survey 2008 (Choi and Toh, 2010) are then assigned to individual agents according to the enriched synthetic population information in a segmented random sampling approach (see Section 6). In a next step, for each agent whose activity plans features work or education activities, fixed locations to perform such activities are assigned. The gravity model based approach combines information on distance between the home location and potential work locations and the likelihood that a particular work location is suitable to the agent's occupation. Secondary activity locations, i.e. shopping and leisure are again assigned in a random sampling approach based on the prior activity location. Mode choice is attributed in a simple rule based

Figure 2: Structure of the MATSim-T simulation system



manner as this choice dimension is subject to the subsequent iterative learning process. In addition to the activity based demand, special plans are generated from origin destination matrices provided by the Singapore Land Transport Authority (LTA) to cover freight trips, trips between Singapore and the neighboring state of Johor, Malaysia and Singapore and tourists trips. Those plans, however, are not subject of the iterative learning process but remained in terms of start time, mode and origin/destination unchanged.

2.3 The MATSim co-evolutionary learing process

Due to the imposed constraints, i.e. capacity of roads, public transport and capcity and opening times of facilities, the effective utility of a daily plan of one agent can only be determined by the interaction with all other agents. In MATSim, a co-evolutionary learning loop (Holland, 1992; Palmer *et al.*, 1994) consisting of the plan execution, scoring and replanning, is employed to find an equilibrium state. Such a state is reached if the utility for each agent does not noticeably change through variation of the day plans.

The general traffic simulation approach used in MATSim is based on queues (Waraich *et al.*, 2009; Charypar *et al.*, 2007; Charypar, 2008). In this approach links are the active element, which move around cars. Each link contains a queue which stores the entry time of each car. Adjacent links collaborate with each other to assure that the different traffic parameters and elements are simulated correctly. For example link capacity, free speed travel time, intersection precedence and space available on the next link are parameters which are taken into account by the simulation. In addition to the car simulation, MATSim features a detailed simulation of schedule-based public transport Rieser (2010) which is integrated with the car simulation and hence covers interaction between public transport vehicles using public roads and cars.

Each plan is then scored according to the simulation's outcome. The basic MATSim utility function to score plans which is also used for the MATSim model presented in this work, was formulated in Charypar and Nagel (2005) from the *Vickrey* model for road congestion as described in Vickrey (1969) and Arnott *et al.* (1993): a plan's utility is computed as the sum of all activity utilities plus the sum of all travel (dis)utilities.

In every subsequent iteration, a certain share of the agents is selected to clone the executed plan and subsequently modify it using a replanning module. For the Singapore implementation, the following replanning modules are included:

- Choice of activity start time and duration
- Route choice
- Mode choice
- Location choice of secondary activity locations

If an agent has obtained a new plan, as described above, then that plan is selected for execution in the subsequent simulation. If the agent has *not* obtained a new plan, then the agent selects one from the existing plans. With increasing iterations, plans with a high utility survive, while plans with a low utility (e.g. caused by long travel times because of traffic jams) are eventually deleted. At the same time, marginal utility gains from changing activity plan diminish and gradually a equilibrium state is reached.

3 Population Synthesis

3.1 Sources

In absence of a full population census, the agent population is generated using iterative proportional updating (IPU) and weighted random sampling of household survey records. In lieu of a public use micro data sample with matching marginal sums, data from a national travel diary survey (Household Interview Travel Survey, HITS (Choi and Toh, 2010)) which constitutes of a

1% sample of Singapore's permanent population is combined with publicly available breakdowns of Singapore's most recent census. Due to the inconsistency of the scope of the two data sources, the modular framework of the population synthesis is highlighted and thorough cross-validation with independent data is performed.

3.1.1 Controls: Census 2010

Our controls were given at two levels of geographic resolution. These are the Development Guide Plan zones (DGP) used by the Urban Redevelopment Authority and their subdivisions (subDGP). Because the sample is sparse for certain areas, we conducted the synthesis on a subDGP-by-subDGP area. We grouped adjacent areas together where control numbers were relatively small in order to minimise the number of iterations, to arrive at 30 DGP zones (from the original 36 in census) and 92 subDGP zones (down from 259).

On a household level, we used the following controls:

- household income x DGP
- dwelling type x DGP
- household size x DGP

On the person level, controls were as follows:

- age x ethnicity x sex
- income x DGP
- occupation x DGP
- sex x subDGP
- age x subDGP
- ethnicity x DGP

3.1.2 Household Interview Travel Survey 2008

The HITS contains records for approximately 11,000 households in Singapore. The record is for the entire household, including resident domestic workers. All the variable mentioned above were recorded for each household and every person in the household. We stripped the household records of domestic workers to come up with a reference sample, as the control totals from census is for the resident population only.

3.1.3 Non-permanent resident inhabitants

In 2010, approximately 5.1 million people were estimated to have residence in Singapore, of which 3.6 million were citizens and permanent residents recorded in the census. The remaining 1.6 million are workers, tourists and their dependents. Approximately 870,000 persons are lower-skilled workers and tourists, which are not included in the synthetic population. In the transportation model, these persons' activities and movement are derived from a set of special trip matrices provided by the Land Transport Authority (see 6.1.6). The remainder are employment pass holders and their dependents. Very little information is released on this group of people, therefore we made a number of assumptions on their composition based on regulations provided by the Ministry of Manpower, in order to come up with control totals for their synthesis.

3.2 Method

3.2.1 Fitting

The fitting step derives a weight for each household record in each subDGP. This weight indicates the expected frequency of a household with this composition and characteristics in the subDGP, given the distribution of demographic attributes from census control totals. We use Iterative Proportional Updating (Ye *et al.*, 2009) to derive this weight, as it not only considers household controls, but also ensures that person-level controls are matched. Therefore, the procedure will not only produce, say, the correct number of five-person households in a subDGP, but also the correct number of 40-year old male accountants in that same subDGP — given that the numbers of both are provided as control totals.

3.2.2 Sampling

Once the household weights have been derived, we employ simple weighted random sampling to add household and person records to the synthetic population until we come to a total of approximately 4.3 million persons.

3.3 Validation

The synthesis showed very good agreement with all the joint and marginal controls used in the fitting stage, as can be seen from Table 1. We excluded the two controls listed in the last two rows due to the poor convergence they produced during synthesis. To investigate this

Table 1: Validation of synthetic population against controls used in the fitting stage, as well as two joint controls (last two rows) excluded during fitting due to poor convergence

Geographic resolution	Control	Number of categories	Avg control cell value	RMSE	RMSE as pct
DGP	household income	12	3290	66.02	2.0%
DGP	household dwelling type (detailed)	7	6623	306.78	4.6%
DGP	hh size	8	4935	76.71	1.6%
All	pax age x ethnicity x sex	104	34393	645.42	1.9%
DGP	pax income	9	5945	196.66	3.3%
DGP	pax occupation	10	6540	497.02	7.6%
DGP	pax ethnicity	4	32476	1267.58	3.9%
subDGP	pax sex	2	20474	698.05	3.4%
subDGP	pax age	14	2924	109.02	3.7%
All	pax age x sex dwell (simple)	84	44848	5905.59	13.2%
subDGP	pax age x sex x dwell (simple)	84	487.48	229.59	47.1%

deviation, we compared the reference sample against the person age x sex x simplified dwelling type control. Here we can see that the reference sample differs significantly in terms of its covariation structure from the control, which might explain why convergence is hard to attain when also controlling for other important attributes. As there is no information available on the expatriate population, we cannot comment on the validity of the synthetic population beyond the assumptions mentioned before.

4 Generating facility information

Facilities in MATSim are geographic location where activities can be performed by agents at certain moments in time. For the Singapore MATSim model, the individual building was chosen as the level of resolution for facilities. For each facility, information is required on the type of activities (e.g. residential, education, work, leisure) that can be performed, the number of agents that can reside in the facility simultaneously per activity type and the opening and closing times of the facility to capture the temporal dynamics.

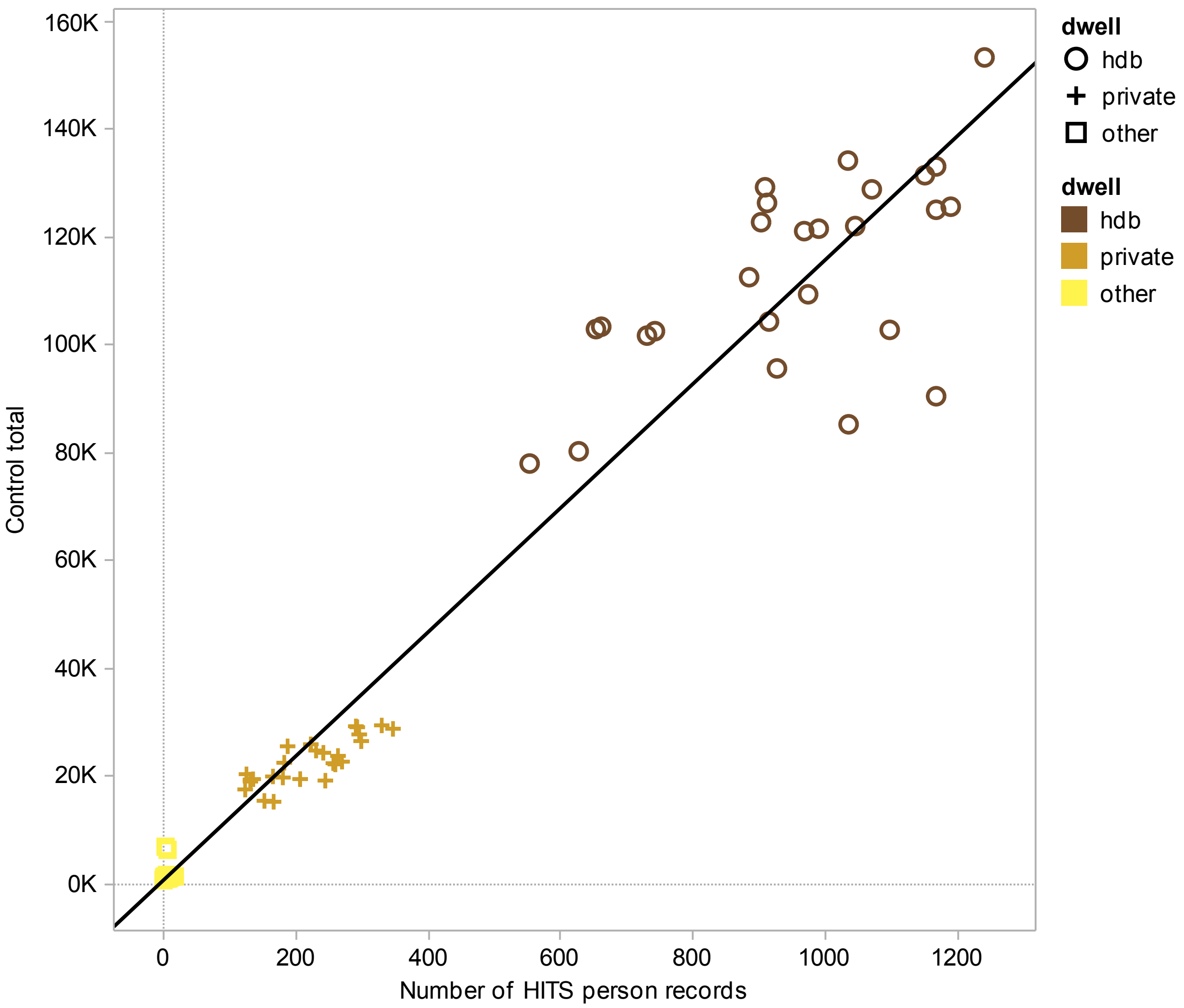


Figure 3: Comparison of relative frequencies of HITS person records vs census control numbers when broken down by simplified dwelling type, age and sex.

This Section discusses the data sources used for facility and activity location generation and in which way this supply is matched to the demand for activity locations.

4.1 Sources

Land use planning Land-use is given by the URA Masterplan 2008. On one hand, the Masterplan provides land-use information on the type of land-use. On other, a gross-plot ratio is provided per plot. The plot ratio of a site is defined as the ratio of the gross floor area of a building(s) to its site area. In the Masterplan a distinction is made between over 20 land-use types, varying from residential to agriculture. For each land-use type, the distribution of attracted occupation types is analysed based on the georeferenced work activities recored in HITS. This distribution is then taken into account when assigning work activities based on the gravity model.

Online resources In addition to the URA Masterplan 2008, several governmental and commercial websites have been consulted for information on land-use and activity locations. A summary can be found in Table 2.

Building footprints Building footprints are available from a navigation network (NAVTEQ, 2011). These building footprints are reverse geocoded with address information based on the building centroids. This makes it possible to assign information from the online resources to building footprints. This makes it possible to compare the points of interest obtained online with the number of building footprints.

Table 2: Data sources available

Facilities		Source	Number
Residential	Public	HDB (2011); AllProperty (2011)	10,041
	Condominiums	URA (2011); AllProperty (2011)	3,008
	Landed	URA landed housing plan	59,619
Work		URA Masterplan	
Education		Ministry of Education (2011), websites of international schools	
Secondary activities		Streetdirectory (2011), Giant (2011), NTUC (2011)	14,965

4.1.1 Facilities

Residential facilities For public housing (HDB for Housing Development Board), the number of units per type is available for the majority of the flats. To a large extent the number of units in the private flats (condominiums) can be found online as well. The number and type of units serves as a basis for the assignment of households to residential units.

Work facilities Initially, work locations were based on points of interest in the categories commercial and industrial. In addition, work locations are also added to education and residential facilities. With the release of the URA Masterplan (URA, 2008), work facilities are generated based on the designation of a parcel and the gross plot ration indication given by the Masterplan. However, in absence of a census of entreprises, apart from the gross floor space for each work facility, no information on the number of work location was available.

Education facilities Locations of primary, secondary and tertiary education is collected from the Ministry of Education. Additionally information on private schools has been gathered. For private schools as well as for higher education, such as colleges and universities, the number of students could be found. This is however not the case for primary and schools. Here the number of students is based on the average number of pupils in Singapore per school type, multiplied by the standard deviation multiplied by random number.

Secondary activity facilities Secondary facilities comprise of a broad set of point of interest based on the activity locations as reported in the Household Interview Travel Survey (HITS) 2008. Points of interests for secondary activity location include supermarkets, malls, markets, food centres, restaurants, sports facilities and parks. Also, a number of residential units is selected as secondary activity location, as a significant part of the sample in HITS reported visits to friends and family. For the moment, generic capacities have been assigned to different types of secondary activity facilities. However, the data framework principally allows specifying a dedicated capacity for every single facility, which could be the result of a shopping mall survey.

4.2 Data integration

4.2.1 Population distribution

The population synthesis described in Section 3 results in a number of households per planning zone per dwelling type. In order to assign the population to residential facilities the following procedure is followed:

- Number of residential units per type (7 types) are summed per planning zone (92).
- Per residential facility a probability is computed by dividing the sum of the units of type i of a facility by the total number of units of type i in zone q.
- For each household residing in type i a residential unit of type i is drawn from the facilities in zone q.

The result of the procedure can be seen in Figure 4, where the bars indicate the number of households assigned per facility and type and the line represents the number of units available. A capacity constrained approach was not applied as the total number of units in reality is unknown.

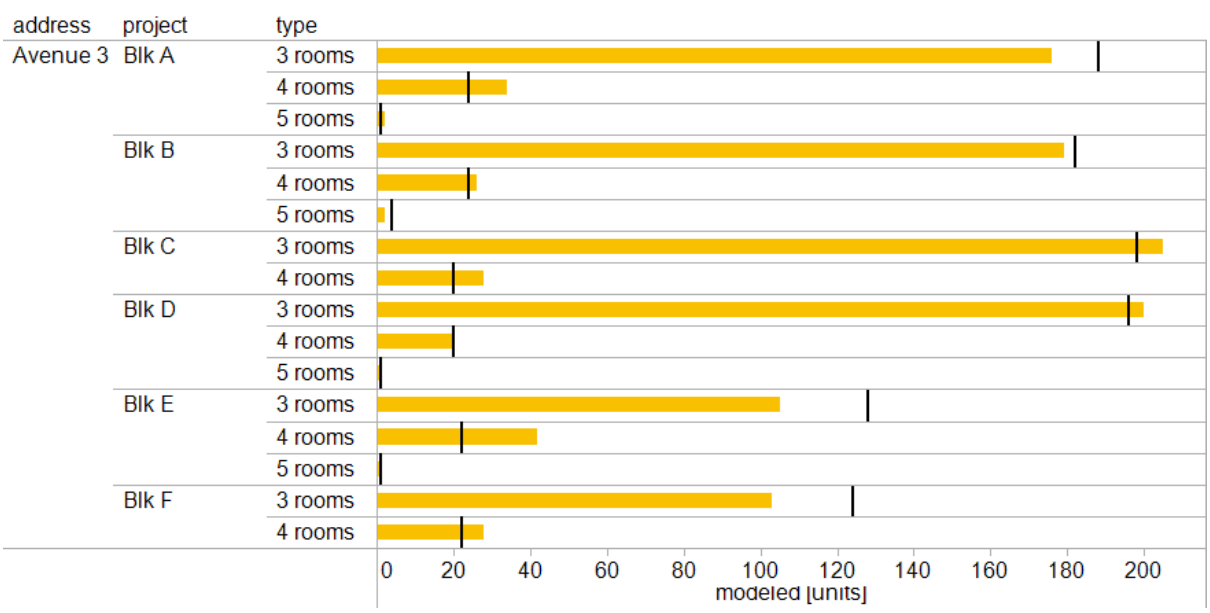


Figure 4: Residential assignment

4.2.2 Capacity of work locations

In absence of an enterprise census or any other data source on the spatial distribution of work locations in Singapore, a new model to estimate capacities of work locations was developed. In a first stage, public transport smart card data (Chakirov and Erath, 2011) is used to detect work activities with a rule based approach: all observed activities with duration longer than seven hours are assumed to be work activities. Using an iterative proportional fitting approach which takes the distance from stop locations to potential buildings and the buildings' potential gross floor area in account, the detected work activities are then linked to single buildings (Ordóñez Medina, forthcoming). In a next stage, capacities of work locations are increased based on the reported number of car trips to work activities. To this end, the zoning system of the Singapore Transport Model was modified by iteratively merging neighbourging zones so that at least 50 observations work activities are available for each zone. Then, the the number of work activities for each building is obtained by inflating the number of work activities detected with the smart card data according to the reported mode share within the according zone. This procedure, however, is currently under review since the building's proximity to a public transport stop affects the number of assigned car-based work activities. Therefore, in future versions of MATSim Singapore, number of work activities will be inflated on a zone level and car based work activities are then distributed to individual buildings using the buildings' gross floor area as a weighting factor.

In addition, the model to detect work activities has been improved. Instead of the rule based approach, (Chakirov and Erath, 2012) propose a Logit model taking into account information on start time, activity duration and density of different land use types around stop locations. This new model perform better in this regard and will be applied in future versions of MATSim Singapore.

It is planned to validate the work location model with data provided by Singapore's Urban Redevelopment Authority. URA's work location information is based the effective gross floor area of buildings and assumptions on the average space required for each work place depending the designated usage of the work facility. However, when this paper was submitted, this information was not yet available.

5 Modeling of car license holdership and car availability

5.1 Approach

Persons generated by the synthetic population do not include a driving license; households do not own a car. In order to add these variables, logit models have been developed to add both a driving license and a vehicle to each person and household of the population.
Two main model approaches based on a discrete choice framework can be found in literature: random utility models and Ordered Logit models. Whereas in the first modeling approach it assumed that vehicle ownership is a random variable, the latter modeling approach assumes that households have a higher utility of owning a vehicle versus not owning a vehicle or driving license (Bhat and Pulugurta, 1998; Potoglou and Susilo, 2008). Based on initial model results and literature, Multinomial Logit (MNL) models were estimated.
Furthermore, it is possible to estimate the probability of the number of licenses and vehicles with separate models, or to estimate these models simultaneously by applying a nested structure, the advantage of the latter being overcoming the correlation between number of driving licenses and number of vehicles within a household. However, we opted to estimate separate models for the following reasons: modularity within the initial demand process, easier to validate market shares and the possibility to 'age' the population in a later stage.
Vehicle ownership and household information are given by the Household Interview Travel Survey (HITS) 2008 Choi and Toh (2010). For this survey 1% of the population is questioned on their travel behavior on a single workday in person. The survey contains 36,978 individuals in 10,641 households. The survey is conducted once every four years and is commissioned by the

Singaporean Land Transport Authority (LTA). HITS contains data on three levels of aggregation. The highest level of aggregation contains household characteristics such as dwelling type, postal code and quantity and type of vehicle available. Second, person characteristics are available such as age, income, profession and employment type. On the lowest level of aggregation information on trips is available such as mode, purpose, cost and time. In 1,533 of the households one or members refused to disclose their monthly income. In total 8,846 cases remain for estimation after controlling for availability of a driving license; several households do have a vehicle available but not a driving license.

5.2 Models

5.2.1 License ownership model

Our final model for driving license ownership on a person level includes variables for dwelling type, income, number of members in household, a dummy variable indicating if a person is employed and a dummy variable indicating if the person is retired. Similar to Ciari *et al.* (2007) several variables representing the utility of having a driving license at a certain age per gender were included. Table 3 shows the parameter estimates of the driving license model. Whereas

Table 3: Parameter estimates driving license model

	No driver license	Driver license*
Constant		-26.6 (-29.91)
HDB small		-0.57 (-11.23)
HDB medium (ref)		-
HDB large		0.486 (11.63)
Condominium		1.27 (17.85)
Landed property		1.82 (23.15)
#members household	0.032 (2.47)	
Age		-0.246 (-30.06)
Age * Male		0.037 (39.56)
Ln (age)		9.65 (29.26)
Income k	-0.103 (-17.13)	
Number of observations	36,492	
Init log-likelihood	-18533.679	
Final log-likelihood	-13021.053	
Adjusted rho square	0.29	

* License available to persons over 17 and non-domestic workers

males have the highest utility of a driving license around 45, females have the highest utility around the age of 35. After this age, utility declines. It is hypothesized, that is due to the transition of Singapore from a developing country to a highly developed country in a short time span. Based on a rho-squared of 0.29, model performance is high.

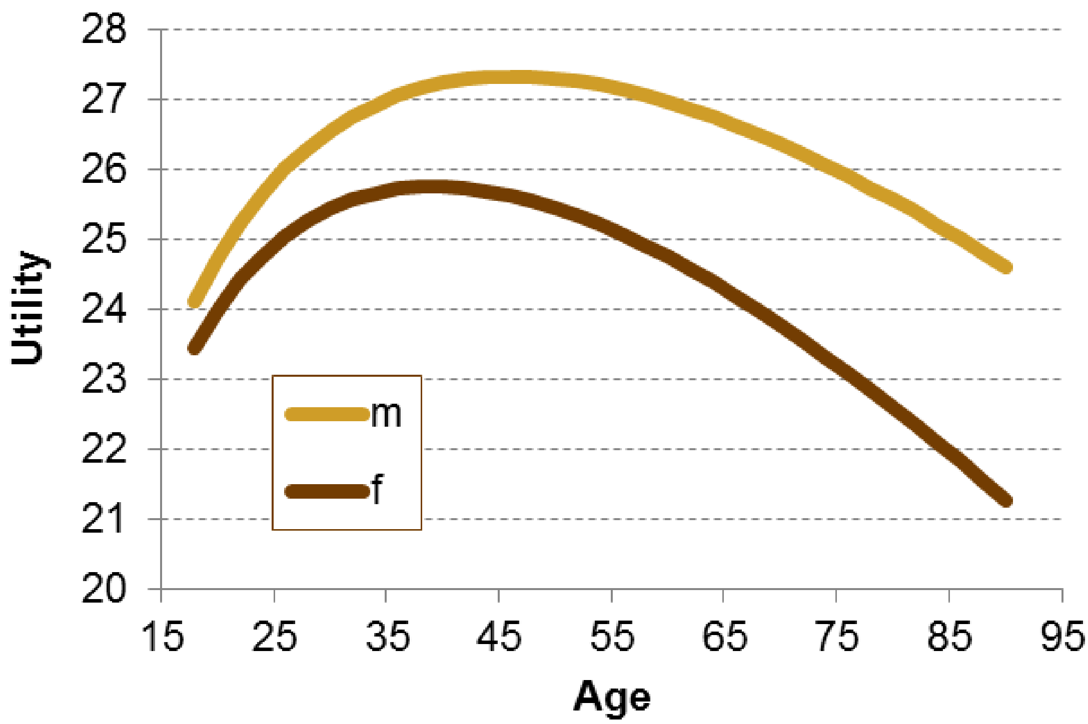


Figure 5: Age vs utility driving license

5.2.2 Car ownership model

The model currently applied in the initial demand process of MATSim Singapore is a MNL model. It contains 18 variables regarding dwelling type, monthly household income, number of children, number of adults, number of driving licenses. To capture the spatial structure of Singapore, a series of parameters indicating the postal sector of the household were estimated. Two alternatives were considered: not owning a vehicle and owning a vehicle. Other modes of transport, such as taxis, light gooded vehicles and motorcycles were omitted because of their small market shares. Judging by the adjusting rho-square of 0.31, model performance is good. Households residing in landed property have the highest utility of owning a car, as do households with a high income. On one hand, this reflects that households residing in landed property need to travel farther to reach amenities like schools, supermarkets and sport facilities. On the other hand, the relative high importance of income reflects the high costs of vehicle ownership and usage in Singapore. The number of children within a household increases the probability of owning a vehicle.

5.3 Validation and application

Both the driving license model and car ownership model have been validated by both examining the market shares observed in HITS. In addition, the results of the car ownership model are compared with the car registry on an aggregated level and presented in Table 4. With the current model, the market shares still deviate from the sample population. This first model has recently been improved by including spatial variables (van Eggermond *et al.*, 2012). This new model perform better in this regard and will be applied in future versions of MATSim Singapore. Figure 6 shows a comparison of the car ownership model applied to synthetic population

Table 4: Market shares of driver license and vehicle ownership model

	Actual sample	Simulated	Simulated model with spatial variables
No driver license	71.1	71.3	
Driver license	28.9	28.7	
No car	58.5	52.6	57.4
Car	41.5	47.3	42.6

described in Section 3. Results of the car assignment have been aggregated to the zonal used by the Singaporean Land Transport Authority. Although there is some variation in difference between modeled and observed varies, no systematic spatial distortion is visible. One reason of for such a pattern might be that some cars are registered for companies and hence georeferenced at the company's location but used by individuals. ï»¿

6 Generating Activity Plans

6.1 Activity Plans

6.1.1 Travel decision

In the HITS, approximately one third of eligible persons did not make a motorised trip on the survey date. This population is generally classifiable by income, age, household car availability and car license. In order to assign a travel decision to our synthetic population, we firstly classify

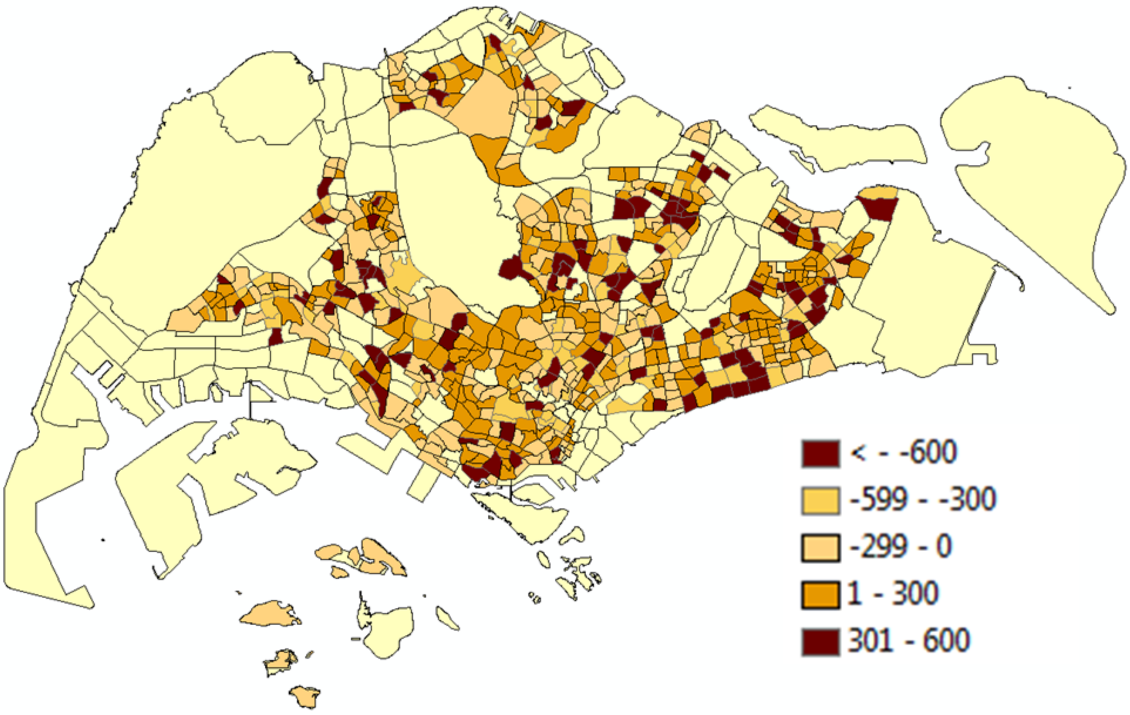


Figure 6: Car ownership: modeled vs car registration, positive value indicates more cars registered than modeled

the HITS person records based on modes of travel used during the course of a day. As we currently model only public transport and car traffic, we add exclusive users of other transport modes to the list of non-travelers. We then produce joint distributions of age x income x car availability x car driver licensure versus a joint travel decision / initial mode choice outcome variable. The variable has four possible values: 1) no travel; 2) exclusive car travel as driver; 3) exclusive public transport travel; and 4) a mixture of car driver and public transport travel. Based on the frequency of these values for each combination of predictors, we assign the travel decision and initial mode choice for each member of our synthetic population, using weighted random sampling.

6.1.2 Activity chain assignment

Activity chains are assigned based on their observed frequency in HITS. We identify the 22 top activity chain frequencies in the survey, and derive their joint distributions by sex, occupation, age and household car availability. Then we assign an activity chain to each member of the synthetic population using stratified weighted random sampling. As our synthetic population includes foreign workers, the relative proportion of worker chains is higher than in HITS. Also, we have a smaller number of chains involving educational activities, as a lot of scholars get dropped off at school, or take the school bus; both modes of transport that we don't simulate.

6.1.3 Primary activity assignment

Work We classify HITS work activities by their start time and duration. The person records are then stratified by occupation, and whether the person performed additional activities before, during or after work. Then a kernel density estimation is performed for each stratum. Where a stratum is too sparse, densities from marginal distributions (occupation x activity chain type) are multiplied. The density estimates are then used in a weighted sampling of start time and duration for each stratum in the synthetic population. The work activity type is then identified by finding the nearest start time and duration to the assigned values.

Education We classify educational facilities in our facilities database as primary, secondary, etc. similar to the classification used in the HITS. Pre-schools are excluded. Then, HITS records are used to generate a joint distribution of educational activity x age x household income. An educational activity is then assigned to each qualifying agent in the synthetic population through weighted sampling, stratified by the agent's age and household income.

6.1.4 Primary activity location assignment

Primary activity location assignment is done on a per-agent basis.

1. For each agent, a sample of 1000 qualifying facilities are drawn;
2. An 'attractiveness' weight is derived for each facility, based on a gravity assignment type strategy.
3. For work activities, weights are attenuated by multiplying each weight with the relative probability of finding the agent's occupation type at the facility's URA land-use type;
4. A facility is then picked from the agent's choice set using weighted random sampling.

Gravity parameter estimation was performed using Euclidean distance, stratified by vehicle availability. If there is a car available in the agent's household, the procedure uses the car parameters for weight estimation, otherwise public transport.

6.1.5 Secondary activities

Where an agent has secondary activities in their activity chain, the procedure for primary activity location assignment is repeated, except that weights are not attenuated before weighted random sampling is performed. Secondary activity location choice is part of the simulation procedure, therefore the initial assignment is of little consequence and is likely to change during the course of the simulation.

6.1.6 Additional activity plans for freight, cross border and tourist travel demand

Additional activity plans for freight, cross border and tourist travel demand are generated from origin destination matrices provided by the Singapore Land Transport Authority (LTA). Those trips cover freight traffic, traffic between Singapore and the neighboring state of Johor, Malaysia and Singapore and tourist trips.

In order to fit the agent based nature of the mobility simulation, the provided matrices need to be converted into single trips. Since the trip matrices have been generated for a zone-based transport demand model the following discretisation process is applied. Firstly, the floating numbers indicating of the origin demand matrices are transformed to integers using random rounding. Secondly, within each zone trips are assigned to facilities a using a weighted random sampling approach, using potential floor surfaces representing the weights. Thirdly, trip start times are generated according to different indications of temporal dynamics: for car trips to and from Johor and freight trips, correspondingly categorized road detector data is available aggregated to 30 min time bins. After spatial aggregation of all count locations, the total number of trips is distributed proportionally to the counts figures within each time bin. To generate trip start times to the split second, uniform distribution is assumed within each time bin. Tourist trips are temporally distributed in a similar way, but observations of visitor dynamics of major tourist attractions are taken into account instead of loop detector data.

Since the plans representing special are not representing activity based daily plans, in the iterative learning process only the rerouting module is employed, whereas start time, mode and origin/destination remain unchanged throughout the process.

6.2 Validation

As the home-work-home activity chain is prevalent in Singapore, making for half of the activity chains in HITS, a validation of work location assignment is important to our model. Figure 7 compares work location assignments with the number of work-bound attractions in HITS by DGP. Our procedure produces more placements away from the city centre, especially in the north and the west. As a consequence, our commuting population tends to travel further than what was reported in the survey. In the following section, we discuss a number of changes to the work location assignment process that should produce a better match with the survey, both with respect to aggregate volumes of jobs assigned to each DGP, and the resulting trip distance distribution.

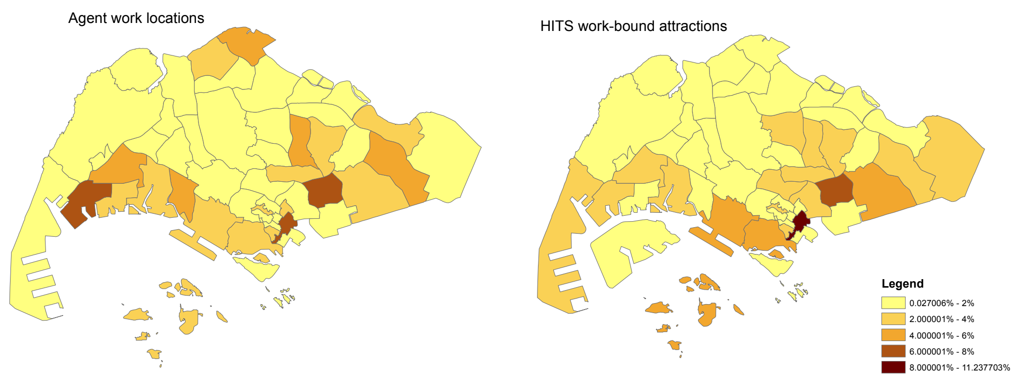


Figure 7: Comparison of agent work location assignment vs. HITS work-bound attractions.

6.3 Outlook

Based on the validation, a number of possible improvements to our initial demand generation process have been identified.

Alternative scheduling using machine learning approach Currently, scheduling is simply done through sampling of the most prevalent schedules given an agent's demographic attributes. No intra-household coordination takes place with regard to maintenance and joint trips and activities, and agent schedules don't display the full gamut of possible activity combinations seen in the survey. An improved scheduling process, possibly incorporating machine-learning approaches such as those put forward by Charypar and Nagel (2006) and Arentze and Timmermans (2009) will be investigated, along with further work on the intra-household scheduling process to model the large share of joint trip-making observed in Singapore.

Work location assignment Currently our gravity model estimation is stratified only by vehicle availability. It has been proposed that further stratification by occupation type would be appropriate. A process whereby an agent is first assigned a work DGP before being assigned a work facility, should produce a better match between our assignment and the expected distribution of workers to centres of activity across the island. Such an assignment approach should at least produce comparable flows at the aggregate level, and thus ensure a better match of trip distances to those recorded in HITS.

Facility capacity is an important component of the work location assignment process, with higher capacity facilities attracting more jobs. The process of deriving facility capacities from EZLink data and mode-shares by transportation zone could be further improved. Currently, facility capacities close to public transport stops are inflated more than those further away. In a sense then, this model favours public transport accessibility in assigning capacities. The method will be adjusted to take account of car accessibility, so that facilities further away from transit stops, but with good accessibility by car, will have their capacities commensurately increased.

Motorized travel decision The reason for not making a motorized trip recorded in HITS are manifold; some people are retired or unemployed or infirm, and don't need to travel. Others walk or cycle to work, implying that they live close enough to work for those travel options to be viable. Others work from home. Once our scheduling and work location assignment methods have been improved, the distance to work, demands of the activity schedule, and the agent's personal means and wants all figure into whether they make use of motorized transport or not. As a result, cycling and walking should be included as mode choices in our model, and form part of the simulation process.

7 Transport supply

7.1 Sources

7.1.1 Transport networks

To match the spatial granularity of the activity demand model, a high resolution transport network model is required. For the Singapore implementation, a high resolution network provided by Navteq featuring directed links is used. Being primarily designed as a network for route guidance, some adjustment was required to make the network suitable for transport demand modeling. First, the original network frequently features several links to represent street shapes. Since very short links are not ideal for queue-based microsimulation because the problematic representation of such links in terms of storage capacity, a transformation routine was applied to simplify the network by merging such row of links together while saving original distances. Second, information about number of lanes, capacity and free speed is included with limited accuracy. Therefore, a methodology for matching two networks was developed to enrich the Navteq network with information from the existing transport planning network. Thirdly, the original Navteq network does not include any public transport information. In order to obtain a multi-model network, a rail network was added by creating one link between each pair of consecutive MRT and LRT stations. The resulting network contains 43'118 nodes and 79'835 links.

For planning purposes, LTA uses a simplified road network model. As conventional transport demand models are designed to compute flows between zones, such simplified network match feature sufficient resolution. However, the network used in the Singapore model is quite extensive and features 12'420 nodes and 26'972 links. Given its main purpose and gradual development, this model provides accurate information on capacity, free speed and number of lanes for principal and secondary streets.

7.1.2 Public transport schedule

In MATSim, the base layer of public transport systems representation is a set of stop facilities and a set of public transport lines. For each line, one can define several routes and each route features a sequence of stops, a path or sequence of links, and a set of departures or services. Each service has a vehicle of a specific type assigned. For each vehicle, characteristics such as type, capacity, size, door system and type of motorisation can be incorporated.

For Singapore the public transport systems information was provided in the General Transit Feed Specification (GTFS) created by Google. Each service of a certain line is defined with a sequence of stops and expected stop times. In addition, the Singapore GTFS information includes GPS traces to indicate the route of bus services between two subsequent stops.

7.2 Supply modeling

7.2.1 Combining planning and high resolution network

To enrich the Navteq network with information from the transport planning network, a semi-automatic map-to-map matching process is applied. In a first stage, an automatic process along the lines proposed by (Balmer *et al.*, 2005) matches intersections between both networks. Since not all nodes necessarily represent intersections, an algorithm that qualified nodes according to topological characteristics is applied: the result are matching groups of nodes that represent one intersection both in the planning and in the high resolution network. In a second stage, the results of the automatic processes are reviewed using an interactive graphic tool. Visualising both network next to each other in split screen mode, it allows a user to navigate and zoom both networks at the same time. The user can also match intersections selecting groups of nodes of both networks, and modify or remove existing matches. Supposing that all the intersections represented in the planning network are matched with the high resolution network, in a third stage, another automatic process is executed. It matches paths (sequence of consecutive links) between adjacent intersections taking into account distances and link directions. This is again followed by a manual process using a modified version of interactive tool. Again, both networks are in split screen, but this time, links are highlighted. To detect unmatched paths or errors in the automatic process, link free speed is indicated by different colors and link capacity by line thickness. By selecting paths from both networks, one can modify or remove matchings. After matching all paths between intersections, capacities, free speeds and number of lanes , information form the planning network is then automatically assigned to the high resolution network. Finally, corrections on the enriched high resolution network are manually edited by visual inspection using the tool's single screen option. Video demonstrations of the tools are accessible at (Ordóñez Medina, 2011d,c).

7.2.2 Electronic road pricing

The MATSim framework provides the functionality to simulate various types of road pricing scheme, including dynamic cordon tolls like Singapore's Electronic Road Pricing (ERP) scheme which feature time and vehicle dependent road toll. Based on two data sets indicating the location and time dependent toll levels, the links corresponding to the 69 gantries were manually identified and specified with the prevailing tolls.

7.2.3 Traffic lights

Without specific information on traffic lights, at intersection where spillback occurs, the queue based traffic simulation in MATSim priorises approaches probabilistically but does not specifically cover green time fractions (Cetin, 2005). Using the approach proposed by (Grether *et al.*, 2012), a link leading to an intersection is dissolved to several links to represent the layout of turning lanes. Green time fractions can then be attributed to each newly generated link according to prespecified signal plans. Whereas the location of signal controlled intersection was available, time dependent signal plans remained inaccessible with reasonable effort due to the proprietary format of the signal control software. Thus, so far traffic lights are not specifically included in the presented MATSim Singapore implementation.

7.2.4 Map matching public transport routes

To facilitate interaction between buses and cars in the simulation model, scheduled bus services available in the GTFS format need to be map matched to the navigation network. To this end, a semi-automatic map matching procedure was developed (Ordóñez Medina and Erath, 2011). In a first stage, the following automated steps are processed. Locations of bus stops are matched to a set of potential links according to the perpendicular distance between the stop coordinate and the candidate link. Then the shortest path between each pair of candidates is calculated finally. To include also the information provided by the GPS traces, the shortest path algorithm takes the distance between tracing points and links into account by modifying the travel cost of each link. By selecting the shortest path between the two stops, the stop to link relationships are determined. In a second stage, an interactive tool displays the results of the first stage and offers tools to modify the path and the stop-link relationships. The original network is displayed and full navigation tools are provided as well. If according to the visual representation the relation between bus stop and link needs to be adjusted, this has implications to all bus lines serving the given bus stop. Since only unique relations between bus stops and links are allowed, all routes leading over a stop whose link relation is modified are erased and have to be processed again. To ensure the quality of the results, the tool also features verification routines that check important properties of the solution, like connectivity, order, completeness or u-turns. Once all routes are in ordere, the tool allows saving the edited version into MATSim public transport systems model XML file. A video demonstration of the tool is available at (Ordóñez Medina, 2011b).

7.2.5 Bus lanes

On certain roads in Singapore, one lane is dedicated for bus use only. Two categories of bus lanes exist: full day bus lane on which cars are only allowed between 8.00pm and 7.30am or on Sundays and normal bus lanes which operate during weekdays from 7.30am to 9.30am and 5.00pm to 8.00pm. To cover bus lane availability in the transport simulation, the road network was modified to model the availability of dedicated bus lanes. New links were added to the network with the same coordinates but different mode restrictions. For example, instead of having one link with four lanes allowing bus and car vehicles, two links with different characteristics are generated. On the exisiting links, now only cars are allowed and features a three lanes capacity. On the new additional link, capacity is set to one lane and only buses are allowed. To cover competition caused by turning vehicles, this new sequence of links is then connected to the network to nodes that represent intersections. As the information is only provided in a text form an interactive tool was developed. It allows to select the initial and final nodes of the exclusive bus lane, calculates the shortest path to assure that the correct street is selected and automatically executes the idea mentioned above. As only the name of the streets is provided, but no coordinates, a high resolution graphical map is used as background layer. To help finding the relevant area in the map efficiently, the map can be centered by entering the street name. For this feature an automated query using GoogleMap API was implemented. A video demonstration showing the functionality of this tool is accessible at (Ordóñez Medina, 2011a). With the current implementation, bus lanes are assumed to be in operation during the whole day. Since congested condition arise during the peak hours where both full day and normal bus lanes are in operation, such a simplified consideration only affect only off peak hours where actual road capacity is underestimated. However, most links that feature bus lanes feature three or more lanes, the effect of modeled traffic conditions is expected to be low.

7.2.6 Vehicle types

The GTFS information does not include any information on the vehicle type for individual bus and MRT deployments. Rolling stock information for the MRT and LRT system was used as available on dedicated Wikipedia pages. Information provided by SGWiki on capacity and layout was used to specify buses. Since several types of buses are used on single lines, for each bus line, all listed bus types were assigned to individual deployments with equal probability.

7.2.7 Dwell times

MATSim provides two types for simulating boarding and alighting processes from and to public transport vehicles. For MRT, dwell times are obtained by multiply the number of boarding and the alighting passengers using flow constants, as both processes can be performed in parallel. For buses, in Singapore, front and back doors are exclusively used for boarding and alighting, respectively. Therefore, the longer of those two durations is considered as the total dwell time.

7.3 Outlook

Traffic lights Instead of the manual recoding traffic signal plans into the MATSim format, another strategy is envisaged. By adapting green time shares to simulated demand, the operating signal plans who also switch dependent on demand distribution can be mimicked. Changing signal plans however is expected to affect transport behavior, at least in the dimension of route choice. Therefore, an iterative process would be required equilibrate changing signal plans and demand reactions.

Bus lanes With the current implementation of bus lanes, we assume that bus lanes are for exclusive usee of buses throughout the whole day. However, in future implementation cars will be forced off from using the bus lanes during operation by imposing exceptionally high cost for traveling on such links. Such an approach reflects the actual circumstances, where cars are charged fines for using bus lanes during operation hours.

Dwell times In a recent study, (Sun *et al.*, 2012) propose based on an analysis of transport smart card data collected in Singapore a new model for takes into account the observation that passengers only board at a constant rate when the number of passenger below a certain level. Statistically different boarding rates and criticality levels were estimated for different bus types. It is planned to adapt this model for MATSim which requires only minor code extension. In the current version of MATSim, boarding and alighting processes at public transport stops are exclusively performed sequentially. However, a number of stop facilities are actually designed to allow parallel dwell process of two or three buses. To adequately represent such situations, modifications in the stop facility model and in the boarding and alighting processes are required. Besides this, information on the effective design of bus stop facilities in Singapore need to be obtained.

8 Implementation and Validation

8.1 Implementation

8.1.1 Execution

The simulation used for executing activity plans of MATSim Singapore is based on a time step based parallel queue simulation as presented in (Dobler, 2010). In this model, each road segment is modeled as a First In, First Out waiting queue, with a minimum service time of the length of the road segment divided by the maximum travel speed. Due to the time step based approach, the computational intensity scales linearly with the number of links in the network and is independent of the number of agents. Congestion and spillbacks are modeled through the link capacity information. The maximum number of vehicles that a queue can release equals the predetermined flow capacity, the maximum number of vehicles that can be stored in a link is given by the storage capacity.

To simulate public transport, transit drivers are introduced whose routes follow a predefined schedule and allow other agents to board and alight (Rieser, 2010). Based on the mapping of bus service routes to the road network, physical interaction between buses and cars is simulated (two video animations showing buses moving through congested parts of the network on links with and without dedicated bus lane are accessible at (Erath, 2011b,a). The output of the simulation is a so-called events file which documents all simulated state changes for all agents. State changes include start and end of an activity, enter and leaving a link or public transport stop and vehicle. For the 25% sample of the Singapore scenario (see section 8.1.4, in every iteration around 117 millions events are generated. As a result of the complete integration of the simulation in MATSim allows direct handling of event information from RAM for subsequent model steps such as scoring and replanning.

8.1.2 Scoring function

Daily plans are evaluated with a measure of general utility. The employed scoring function follows the model presented in Charypar and Nagel (2005) and combines additively utility gains from performing activities and losses from traveling between activity locations. For each modeled activity type (Section 6.1) both a minimal and optimal activity duration are predefined according to the observations in HITS.

In addition, the score of performing shopping and leisure activities is discounted according to the crowdedness of the related facility (Horni *et al.*, 2009).

In absence of a discrete choice parameters estimated based on entire activity plans along the line of (Kickhöfer, 2009) or (Feil, 2010), generic parameters that already produced meaningful results in for MATSim implementations are applied. The marginal utility of performing activities is set to 6 SGD/h, with late arrival punished with a disutility of -18SGD/h.

Travelling between activities is scored with subject to the travel mode. The according parameters are derived from LTA's travel demand model. For car, dedicated parameters for the cost of driving, tolls and travel times are employed. Similarly, public transport trips are scored according to travel time, number of transfers, walking distance from and to stops and fares which are computed based on the actual distance based fare scheme.

8.1.3 Replanning strategies

In the presented MATSim Singapore model, in every subsequent iteration, for 40% of all agents, a copy of the executed activity plan is generated. This copy is then changed using one of following replanning modules at which each module is selected with equal probability:

Time mutation The time mutation module varies randomly the departure times and durations of activities in a daily plan. Based on experience from other implementation, maximum extent of the shifts was restricted to +/-50min.

Rerouting All trips are rerouted according to the shortest paths according to the loaded network of the prior iteration.

Mode choice For each subtour of an activity plan, the mode is changed. Since the presented version of MATSim Singapore only include car and public transport trips, mode is altered between those two options.

Assignment of secondary activity locations Based on the given locations of the primary activities, and the potential facilities suited to perform secondary activities, the employed destination choice module is based on Hägerstrand's time geography (Hägerstrand, 1970): secondary activity locations are chosen within the region restrained by travel time budgets as defined by the time allocation module (Horni *et al.*, 2009). Within this region the choice is performed based on the MATSim utility function.

8.1.4 Computation intensity

To reduce the RAM intensity of the scenario, a 25% sample of the entire population is simulated. To ensure realistic traffic flows, also the flow and storage capacity of road links are adjusted. Whereas earlier, car-only simulations would typically use a sample population of 10%, the share of 25% was chosen to prevent artefacts when simulating public transport. Hence, the capacity of the smallest bus types of 72 is reduced to 21 passengers, which is believed to minimize random artificial incidences of bus overcrowding.

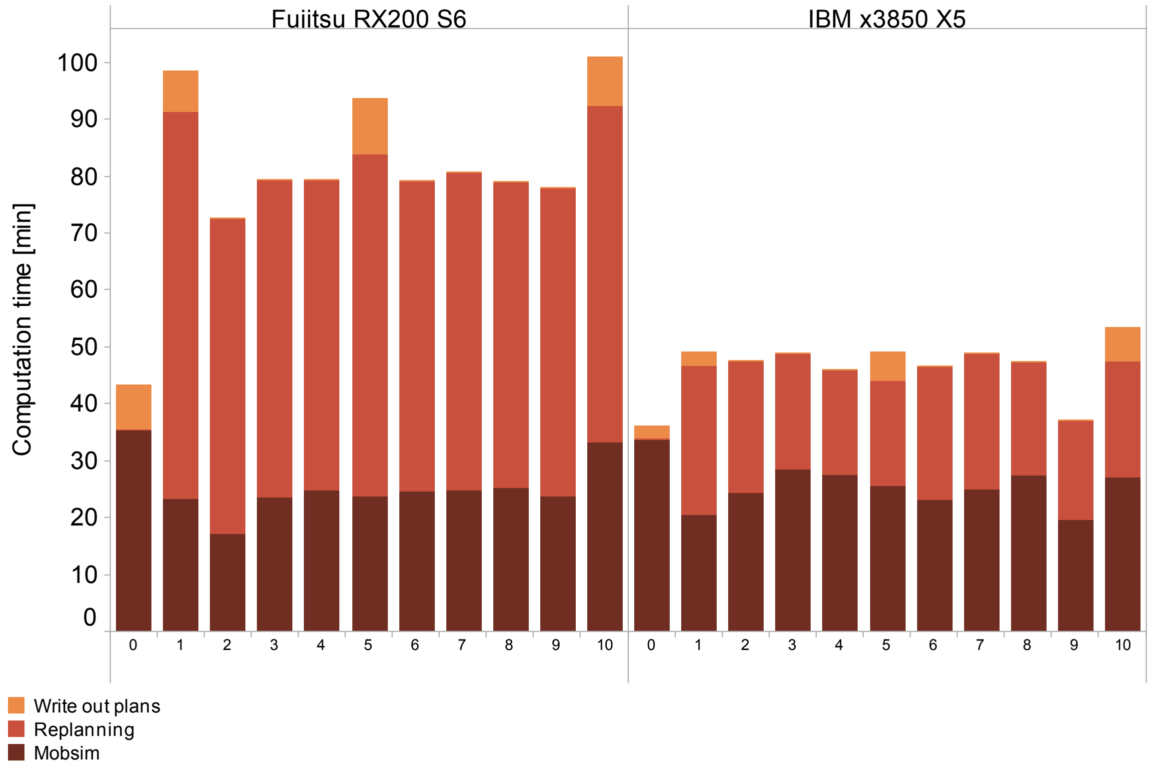
Performance runs were executed on two high performance computation servers:

- System 1: Fujitsu RX200 S6 with 2 Intel Nehalem-EP CPUs clocked at 2.67 GHz each featuring six cores (double threaded) and 144Gb Ram. For simulation runs, 60 Gb RAM were assigned, 24 threads are used for replanning and four threads for the traffic simulation.
- System 2: IBM x3850 X5 with four Intel Westmere-EX CPUs clocked at 2.4 GHz each featuring ten cores (double threaded) and 500Gb RAM. For simulation runs, 60 Gb RAM were assigned, 72 threads are used for replanning and four threads for the traffic simulation.

Figure 8 shows the computation time of the first 10 iterations for both servers. The mobility simulation takes in average about 25min on both system, system 1 being slightly faster due to the higher clock speed. For the replanning procedure, the 72 threads assigned with system 2 pay off and decrease computation time substantially. The performance runs configuration foresees writing out of plan files every fifth iteration which is also performed in parallel processes. In total, ten iterations take 14.1h on system 1 and 8.1h on system 2, respectively. It has to be noted, however, that both runs were not performed on laboratory conditions as on the same time other processes running on the systems might have interfered, e.g. by accessing hard disk drives.

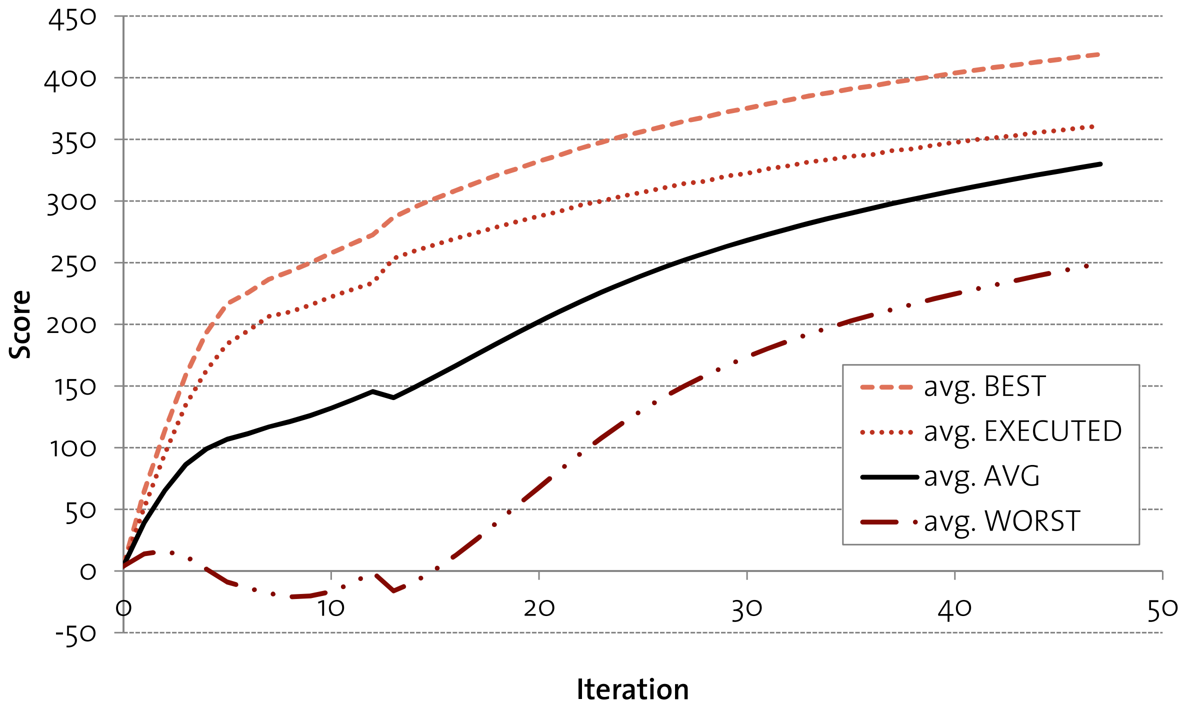
According to the experience with other large-scale MATSim implementations, around 200 iterations are needed for the system to reach a relaxed state. At the time of writing, however, only a couple dozens iterations have been computed so far. The development of the relaxation process is depicted in Figure 9. Given the slope's gradient, it is obvious that the system is not yet near a relaxed state and further iteration are needed. Assuming 200 iterations, in total computation time is expected to amount to more than eleven hours for system 1 and 6 hours for system 2, respectively. Since such a performance is not very satisfying, the following options to accelerate to process are considered:

Figure 8: Computation time for MATSim Singapore performance runs (first ten iterations)



- A characterization of modules is whether they modify a plan randomly (Random Mutation) or whether they search for the best solution based on the results of the last traffic flow simulation (Best Response). Despite being computationally more expensive, it was demonstrated that best response modules usually help to relax the system much faster (Balmer *et al.*, 2009b) . Currently, the only best response replanning strategy is rerouting. Employing replanning modules that not only optimise one aspect of a daily plan, but all parts at the same time using genetic algorithms such as Planomat (Meister, 2011) or Planomat X (Feil, 2010) would potentially reduce computation time substantially.
- Currently, after every replanning stage a mobility simulation is performed. Another approach to simulate traffic flow less frequently. Assuming the outcome of the mobility simulation affects the scheduling and location choice of activities only partly, such a strategy has a great potential to reduce computation time substantially. First trial runs that simulate traffic only every 10th iteration show very promising results as the results seems very comparable with the conventional approach, but are obtained in much shorter time.

Figure 9: Relaxation process for MATSim Singapore (first 47 iterations)



8.2 Validation

When submitting this paper, no steady state solution that would allow meaningful validation was available. Therefore, in this section only an outline of planned validation procedures is presented.

Distributions of trip distance and duration As in the case with aggregated transport demand models, comparing trip distance distributions of the simulated demand with observed trips, for Singapore as reported in HITS, is central to control the validity of the results. By analysing trips from and to primary activity locations, the plausibility of the spatial distribution of home and work facilities is tested. Furthermore, indication of travel times allow a first verification of the transport supply model and traffic simulation.

Road counts In addition to reviewing daily link volumes in the network, the validation with road counts allows to check the modeled dynamics of travel demand over a day. Road count data was made available in hourly interval by LTA for 200 count stations. To exclude effects cause be certain special events, the data draws from several weeks of observation.

Mode choice To test the appropriate function of the mode choice model parameters and replanning module, mode shares for different distance bins and trip purposes as observed in the simulation are opposed with corresponding values based on reported trips. If systematic differences are observed, one can either adjust the constant or individual parameters such as valuation of travel times. However, such a procedure requires careful experiment design as the testing a set of different parameter combinations is computationally extensive.

Travel speed By comparing simulated travel speed with observed values using for example floating car data, both the validity of the road network model and the demand and hence link volume dynamics can be tested on a network wide level. To monitor traffic, LTA gathers speed information collected by taxis. Given Singapore's large taxi fleet, a vast amount of travel speed data could be at hand for validation.

Scenario evaluation The opening of the fourth and fifth stage of the Circle Line (MRT) on 8th October 2011 as well as another extension by two additional stops on 14th January 2012, provide a great opportunity to test the models abilities in terms of predicting effects of mode, route and secondary activity location choice.

9 Conclusion and Outlook

The main challenges of the implementation of MATSim Singapore were twofold: First, collecting and processing input data that allows a fully dynamic transport demand model featuring interaction between public and private transport with the individual building as the level of spatial resolution required innovative data modeling approaches. However, for various sub-models potential for improvement has been identified and possible solutions formulated.

MATSim Singapore is the first implementation to feature integrated public transport simulation, secondary location choice, road tolls and using the individual building as the level of resolution for facilities in one in single model. Areas for improvement in that respect are mainly seen in improving the interplay of replanning modules and its consistency with transport behaviour models, in particular for scoring and routing. The currently implemented public transport router, for example, only takes into account schedule information. Consequently, the same route which might be optimal according to the schedule but might lead over notoriously congested links is chosen in the iterative process over and over again. At the same time, the rather high share of captive public transport ridership and constraints imposed by fixed work location and opening times may limit the effectiveness of other replanning strategies. Together, this might lead to biased service loadings and hence travel times. To overcome this problem, consistent scoring for replanning and traffic simulation would be required. Such an approach would also allow to include the indication of crowdedness and effective waiting times which both have repeatedly proved to affect route and mode choice in travel behaviour surveys.

MATSim Singapore will be further improved along the lines stated at the end of the individual sections in this report. The model is the starting point of a extensive research project which addresses the questions of managing, planning and optimising the flow of people and goods at different time scales and the interaction of these aspects with all elements of a future city Axhausen and Erath (2011). On the medium term scale, the addressed research questions are how to use a model like MATSim to optimise road toll schemes, how to account for coordination among agents, e.g. within a household and how to expand the scope from daily to weekly activity plans. On the long term scale, the research is organised on three pillars, namely, objective fine location choice, service provider agents and social network geographies. Together, this will form the framework of forecasting future states of the cities by updating the spatial distribution of activity locations, the populations demography and transport infrastructure.

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