# Generic Mobility Simulation Framework (GMSF)

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## ABSTRACT

Vehicular ad-hoc networks with inter-vehicular communications are a prospective technology which contributes to safer and more efficient roads and offers information and entertainment services to mobile users. Since large real-world testbeds are not feasible, research on vehicular ad-hoc networks depends mainly on simulations. Therefore, it is crucial that realistic mobility models are employed. We propose a generic and modular mobility simulation framework (GMSF). GMSF simplifies the design of new mobility models and their evaluation. Besides, new functionalities can be easily added. GMSF also propose new vehicular mobility models, GIS-based mobility models. These models are based on highly detailed road maps from a geographic information system (GIS) and realistic microscopic behaviors (car-following and traffic lights management). We perform an extensive comparison of our new GIS-based mobility models with popular mobility models (Random Waypoint, Manhattan) and realistic vehicular traces from a proprietary traffic simulator. Our findings leverages important issues the networking community still has to address.

## Categories and Subject Descriptors

C.2.1 [**Computer Systems Organization**]: Computer-Communication Networks—*Network Architecture and Design*

## General Terms

Design, Performance

## Keywords

Mobility Models, Evaluation, Comparison

## 1. INTRODUCTION

Research in ad-hoc networks relies mainly on simulations due to the lack of large real-world testbeds. Simulations allow for rapid prototyping of newly developed mobility models in large scale networks. The mobility models employed in these simulations evolved from simple synthetic models to more and more complex ones. In order to gain reasonable results from simulations highly realistic mobility models are a prerequisite. Traces of the real world behavior of mobile nodes are the best representation of reality but are difficult to obtain. Today there exists a large number of different mobility models and a set of tools to generate mobility traces based on these models. However, it is often difficult to perform a fair comparison of different mobility models due to different formats for input and output data.

We present the Generic Mobility Simulation Framework (GMSF), a generic and easy expandable framework for the comparison of mobility models. GMSF allows generating mobility traces using any of its implemented mobility models. These traces can then be exported to various trace formats. GMSF also allows defining data communication patterns which can be exported. In order to achieve realistic simulations, GMSF provides several radio propagation models. Lastly, GMSF allows to analyze mobility traces and the network topology using a set of provided metrics. GMSF is designed to ease the further development of additional mobility models or modules extending the framework with additional functionalities.

GMSF implements classical mobility models [3] (i.e., Random Waypoint, Manhattan) and new GIS-based models relying on maps from the Swiss Geographic Information System (GIS) [15]. It also generates traces from the Multi-agent Microscopic traffic Simulator (MMTS) [12, 8], a simulator from the Intelligent Transportation Systems (ITS) community designed by Kai Nagel (at ETH Zurich and now at the Technical University at Berlin, Germany). MMTS is designed to model public and private traffic in all Switzerland at a very fine grained precision.

The ad hoc networking community has proposed a number of vehicular traffic models. City Section [3] and Vehicular mobility [13] address mobility in modern towns based on models from the transportation community. Note that one of the authors has already proposed a simplified vehicular model of the GIS models proposed in the sequel [2]. A number of frameworks are also proposed. Kim and Bohacek [6,7] propose the UDel framework dedicated to urban mobility in the central core of cities. They realistically model both indoor and outdoor pedestrians as well as vehicular traffic based on surveys from many fields. Choffnes and Bustamante proposed an integrated network and vehicular mobility simulator named STRAW [4] based on JIST/SWANS [1]. The closest framework to ours is VanetMobiSim proposed by Bonnet et al. [5] which also allows importing real maps.

The remainder of this paper is organized as follows. In Section 2, we present GMSF and its modular design. Section 3 describes our new mobility models. Then, in Section 4, we give an overview of the set of metrics provided in GMSF, compare mobility models with a subset of these metrics, and draw interesting conclusions for the networking community. Eventually, we conclude this work in Section 5.


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## 2. GMSF

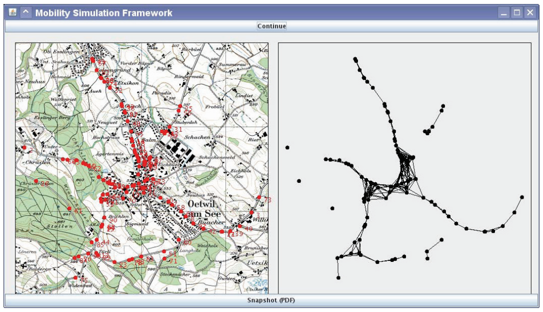



**Figure 1: The Visualization Module of GMSF**

The Generic Mobility Simulation Framework (GMSF) is designed as a generic and extensible framework to model, simulate, and analyze node mobility for wireless networks. It is designed to work together with commonly used network simulators. In order to be easily extended with additional functionalities, GMSF adopts a modular design. A set of configuration parameters allows users to define which modules should be activated and to set the module parameters. Figure 2 shows the basic components and modules of the framework.

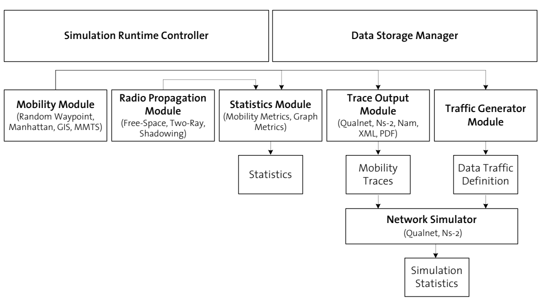



**Figure 2: The Modular Design of GMSF**

GMSF relies at its core on a *Simulation Runtime Controller* and a *Data Storage Manager*. The former is responsible for the initialization of all enabled modules and the scheduling of tasks provided by these modules. Besides, it is responsible for specific mandatory tasks e.g., definition of node positions, output formatting, and visualization. A snapshot of the visualization front-end is shown in Fig. 1. The latter provides modules with access to simulation relevant data (e.g. configuration parameters). It keeps an up-to-date list of all nodes currently in the simulation area. Furthermore, it maintains a log of all mobility events generated throughout the simulation period.

At a lower level, the mobility module and the radio propagation modules provide models for node mobility and radio propagation and are hence mandatory modules of GMSF. All modules are shown in Fig. 2 and detailed in the sequel.

### 2.1 Mobility Module

The Mobility Module is a core module of GMSF. It is responsible for the dynamic instantiation of mobile nodes that either follow a defined behavior (i.e., mobility model) or replay traces. Node mobility is modeled by mobility events which are bounded to a specific simulation time and have assigned a certain duration. Entity-based mobility models (e.g. the Random Waypoint model) employ events which start and end at arbitrary time during the simulation. Microscopic mobility models (e.g., GIS models with car-following), in contrast, generate only events which define node mobility within the current sampling interval, since the next movement of a node also depends on the position of other nodes at the next sampling time. Finally, trace-replaying models employ events with a period depending on the trace's granularity.

Each node has its own queue of mobility events. Mobility events are generated by the mobility model (or mobility trace) and inserted in the event queue of the corresponding node. The node processes all its pending mobility events to update its current position in the simulation area[1].

Currently, GMSF supports Random Waypoint, Manhattan, GIS-based, and MMTS models and more are to come. Besides, it is able to read any common trace format.

### 2.2 Radio Propagation Module

The Radio Propagation module is also a core module of the simulator. It is used to determine neighbor nodes within the communication range. Two nodes are in communication range if one node can transmit a radio signal and the power of the received signal at the other node is above the receiver sensitivity threshold. This calculation is performed by employing the radio propagation model currently instantiated.

The current implementation of GMSF contains the Free-Space model, the Two-Ray model, and the Shadowing model. Other radio propagation models can be easily included as pluggable modules.

### 2.3 Statistics Module

The Statistics module is used to analyze the mobility behavior of nodes using the metrics presented in Section 4. This module has access to all attributes of mobile nodes currently in the simulation area. Two type of metrics are included, (i) mobility metrics which operate only on the current position, speed and moving direction of a node and (ii) network related metrics which operate on the network graph built by employing the radio propagation module to determine communication ranges of nodes. The Statistics module collects and outputs statistical data for different metrics detailed Section 4.

### 2.4 Trace Output Module

The Mobility Traces Output module exports the position information of mobile nodes to a specific trace format. GMSF can export mobility traces for Ns-2, Nam and Qualnet. Additionally, traces can be exported to a generic XML format and to a PDF document. the XML structure has been designed to be easily converted into different representations depending on users needs.

### 2.5 Traffic Generator Module

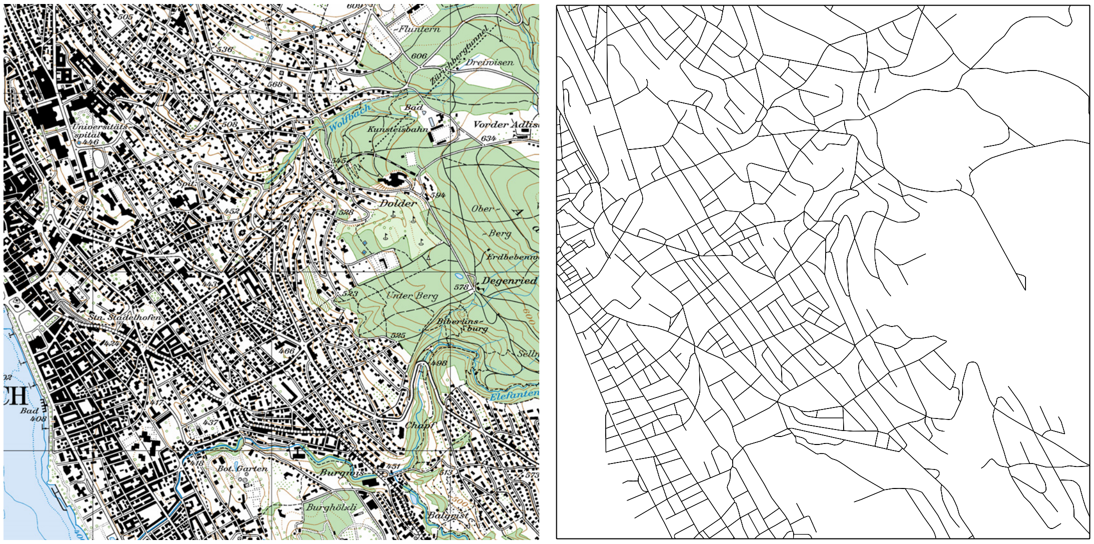
The Traffic Generator module generates a file defining the data traffic which should be transmitted between network nodes in the simulation. Data traffic defined by this module depends on the application scenario and is usually generated according to a specific traffic pattern, e.g. packets are only sent between a fixed number of source-destination pairs with a constant data rate.

## 3. MOBILITY MODELS

Here we detail the different mobility models implemented in GMSF as well as their respective parameters used to represent vehicular traffic.

GMSF implements classical mobility models [3] (i.e., Random Waypoint, Manhattan) and new GIS-based models re-

[1]In fact, only the position of a node at the sampling points is relevant since this position is used by microscopic mobility models and when calculating mobility-related and graph-related metrics.



(a) Vectorized map (b) GIS street topology map

**Figure 3: Vectorized map of downtown Zurich (left) and the associated GIS street topology (right). Maps are reproduced with authorization by Swisstopo (BA071556).**

lying on the so-called maps from the Swiss Geographic Information System (GIS) [15]. GMSF eventually implements the Multi-agent Microscopic traffic Simulator (MMTS) [12, 8], a simulator from the ITS community..

Whether it's for the GIS or MMTS models, GMSF can generate traces based on the street topology of three different areas in Switzerland corresponding to city, urban, and rural scenario. Specific parameters for each model are described in the sequel.

## 3.1 Random Waypoint Model (RWP)

The node speed in the Random Waypoint model is uniformly distributed between 9 and 16 m/s covering the speed limits of the different road categories present in the simulation scenarios. The pause time between subsequent trips is uniformly distributed between 0 and 10 seconds to simulate a short stop at the destination. The initial values for a node's position and speed are set according to the steady-state initialization method proposed by Navidi et al. [11].

## 3.2 Manhattan Model (MN)

The road topology used for the Manhattan Model is a grid consisting of horizontal and vertical roads. The distance between two road intersections is set to 200 meters. Nodes travel at speeds between 12 and 14 m/s. The upper speed bound corresponds to the speed limit of roads within settlement areas in Switzerland. The acceleration is uniformly distributed between -0.1 m/s$^2$ and 0.1 m/s$^2$. If the distance to the front vehicle is less than 25 meters and the current speed is higher than the speed of the front vehicle, the speed is limited to the front vehicle's speed. Since there exists no analytical method to start in the steady-state, the initial 5,000 seconds of the simulation are discarded.

## 3.3 GIS Models (GIS, GIS-F, and GIS-F-T)

GIS models rely on GIS maps. These GIS maps provide a highly detailed representation of the Swiss street topology with a precision of 1 m. Our GIS-based models are behavioral microscopic models that generates steady-state random trips on this real street topology. Fig. 3 represents a vectorized map of Zurich downtown and the associated GIS map of the street topology. The road network for the three scenarios are extracted from geographical data (GIS) corresponding to the simulation area. Only roads which are accessible by vehicles are imported into the road topology of the GIS mobility models. The speed limit for each road is set according to the road category[2].

Three variants of the GIS models exists with with the following micro-mobility settings:

- GIS: nodes perform random trips restricted to the topology defined by the road network.
- GIS-F: nodes perform random trips on the road network graph but adapt their speed to maintain a safety distance to the front vehicle (car-following model).
- GIS-F-T: same behavior as in GIS-F, additionally, nodes take traffic lights into account.

One purpose of defining such variants is to allow us studying the impact of microscopic behaviors on various metrics. One of the authors has pursued a similar study for pedestrian motion in [9]

Since there exists no analytical method to start in the steady-state, we discard the initial 5,000 seconds of the simulation. More details on the GIS models are given in Section 5.

## 3.4 MMTS Model (MMTS)

MMTS is a proprietary simulator from the ITS community designed by Kai Nagel (at ETH Zurich and now at the Technical University at Berlin, Germany). MMTS is designed to model public and private traffic in all Switzerland. It simulates the behavior of a large number of vehicles (autonomous agents) which are modeled as intelligent individuals. Each agent performs trips according to its daily schedule (e.g., go to work early in the morning, go shopping). As such, MMTS is calibrated to closely reproduce

[2]Road categories correspond to the values of the road type attribute in the GIS data model (see Table 1 in Section 5

the real vehicular traffic of Switzerland. Vehicular traces from MMTS are available from GMSF [14] or from [8] in a single trace file containing all nodes in the greater Zurich area. For the three selected scenario (i.e., rural, urban, and city), we extract only the traces of vehicles that are inside or traverse the simulation area during the specified time period. The movement of nodes in the MMTS model is generated according to the extracted vehicular traces.

# 4. EVALUATION METRICS

We now perform a comparison of our new GIS-based mobility models (i.e., GIS, GIS-F, GIS-F-T) with popular mobility models (Random Waypoint, Manhattan) and the realistic vehicular traces (MMTS). We consider the urban scenario with the vectorized map and its corresponding GIS map depicted in Fig. 3. 420 vehicles are simulated in a 3000 m×3000 m urban area. For the radio propagation, we use a combination of the Two-Ray path loss model with an additional shadowing loss of 6 dB. The parameter settings for the physical layer and the employed propagation model result in a communication range of 250 meters.

We first give an overview of the set of mobility-related and graph-related metrics included in GMSF. We then compare the output of the different mobility models with a subset of these metrics. Eventually, we conclude with our major findings.

## 4.1 Metrics Overview

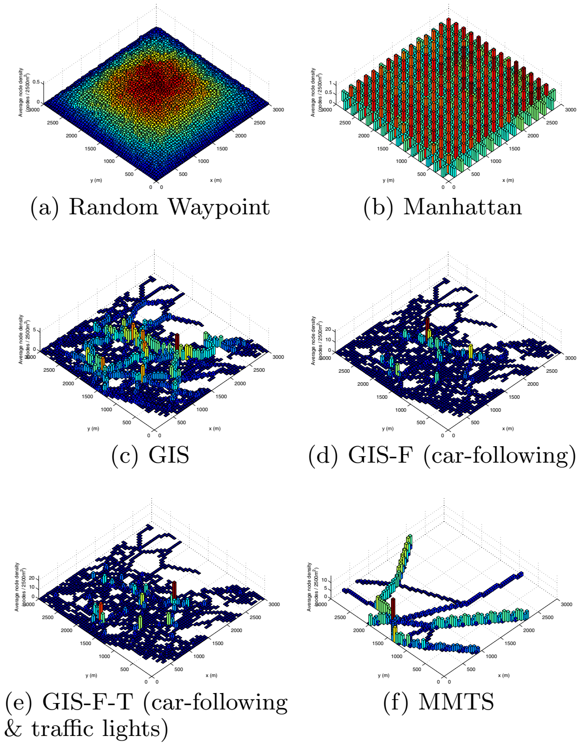
GMSF implements the following mobility-related metrics: Node Density, Distance between Nodes, Distance between Neighbors, Node Speed, Speed Ratio between Neighbors, Relative Movement Direction between Neighbors, Spatial Dependence between Neighbors, Contact Duration, and Paired Inter-Contact Duration. And the following graph-related metrics: Network Graph, Number of Neighbors, Link Changes, Network Connectivity Analysis, and Path Length.

In the sequel of this Section, we retained the most relevant metrics for the comparison of the different mobility models.

## 4.2 Comparison of Node Densities

The distribution of nodes in the simulation area highly depends on the topology restrictions imposed by the mobility model. To measure the average node density, we split the simulation area in 50 m×50 m unit squares. Then, we measure the average number of nodes inside each square throughout the simulation period. The measurement results of the node densities for the Urban Scenario are shown in Figure 4 as two-dimensional histograms.

Histograms for RWP and MN are in agreement with already established results. For the RWP, nodes can be observed in almost every unit square (99.8% of squares covered) during the simulation period. We also note the higher node density in the center of the simulation area which corresponds to the steady-state distribution of nodes consistent with the observations measured by Navidi et al. [11]. For the MN model, the histogram shows that the movement of nodes is restricted to the grid-like road network. The GIS models restricts node movements along the exact course of roads. Therefore, it is only possible to observe a node in about 41% of the unit squares. Compared to the basic GIS model, the car-following extension (GIS-F) and the traffic lights extension(GIS-F-T) do not influence the area covered by node movements but introduce hot-spot regions with higher node densities in the center and in the proximity of traffic lights. Surprisingly, nodes in the MMTS model cover only around 9% of the area since MMTS restricts movement to the major roads. In fact, what is relevant to ITS researchers is to optimize traffic and as a consequence they are only interested where most of the traffic actually takes place, i.e., major road axes.



(a) Random Waypoint (b) Manhattan (c) GIS (d) GIS-F (car-following) (e) GIS-F-T (car-following & traffic lights) (f) MMTS

**Figure 4: Average node density for the different mobility models.**

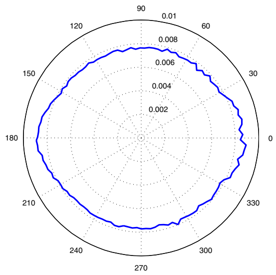
To conclude, we observe that enabling the car-following model (GIS-F) has not a large influence on the number of nodes per unit square. Yet, traffic lights in the GIS model increase the clustering of nodes and lead to a similar node density as in the MMTS model.

## 4.3 Comparison of Relative Movement Directions

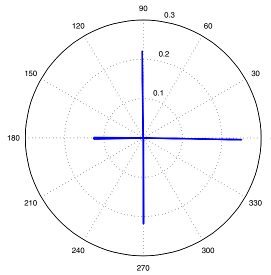
The relative moving direction of neighbors are plotted in polar coordinates in Figure 5. The movement directions of neighbors are uncorrelated in the Random Waypoint model. The plots of all other mobility models show peaks at specific movement directions. The grid structure of the road network in the Manhattan model can be clearly seen in the perpendicular movement directions of neighbors. Neighbors in the GIS models move mainly in the same or in the opposite directions but also to a lesser extent uniformly in other directions. This is a direct result of crossing angles of the road topology. The plot for the MMTS model is highly unbalanced since as already stated before only major axes are taken by vehicles. Besides, traffic flows mainly in one direction during rush hours. We also observe this phenomena with our GIS-F-T model.

## 4.4 Node Speed

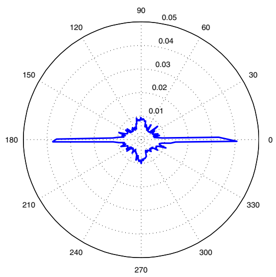
Results of node speed are shown in Figure 6. The node speed in the Random Waypoint model is distributed within the specified speed range. Since it takes more time to complete a trip with a low speed, nodes can be observed with a higher probability at lower speeds. This measurement results are in conformance with the observations made by Na-



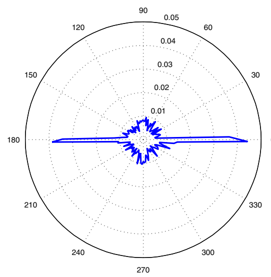

(a) Random Waypoint



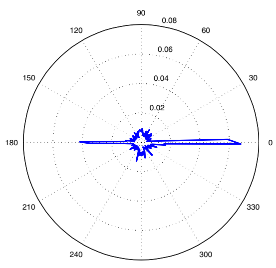

(b) Manhattan



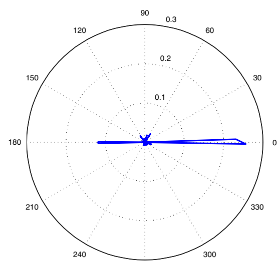

(c) GIS




(d) GIS-F (car-following)




(e) GIS-F-T (car-following and traffic lights)




(f) MMTS

**Figure 5: Relative movement direction of neighbors.**

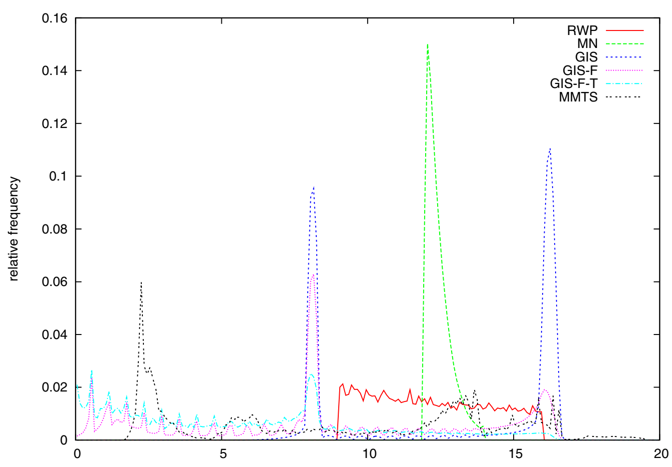



**Figure 6: Relative Frequency of Node Speeds.**

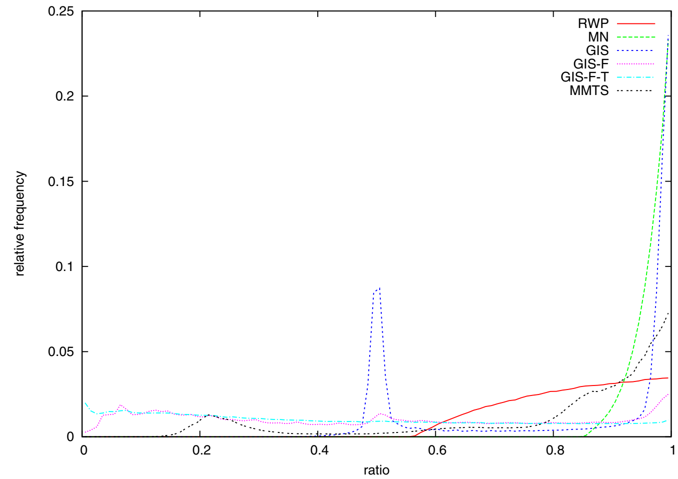



**Figure 7: Relative Frequency of Speed Ratios between neighbors.**

vidi et al. [11] when investigating the steady-state behavior of Random Waypoint. The speed of nodes in the Manhattan model approaches the lower speed bound since nodes have to adapt their speed to the front vehicle to avoid collisions. The two peaks in the GIS models account for the speed limit of the two predominant road categories present in the scenario (see second and last entry of Table 1 in Section 5). Similar peaks are also present in the GIS-F and GIS-F-T models but to a lower extent. The vehicles' speed is more distributed over the whole range since nodes are continually accelerating or decelerating due to the car-following model or traffic lights. A large part of the vehicles in the MMTS model travel at speeds between 12 and 17 m/s. In addition, we measure a peak at around 3 m/s which presumably arise due to high traffic load on certain road segments at rush hours.

The speed ratio compares the node speed to the speed of a neighbor. A high speed ratio corresponds to a small absolute speed difference. We conclude from our results shown in Fig. 7 that the speed ratio between neighbors in the Manhattan, GIS and MMTS models is noticeable higher than in the Random Waypoint model. Yet, no model comes close to the MMTS model and the GIS-F-T model is constant which is counter-intuitive. This point requires further analysis.

## 4.5 Distances between Nodes

Fig. 8 shows the measured distance between nodes which are neighbors. All neighbors are within the communication range of 250 meters. Remarkable is the sharp peak at a distance of around 200 meters in the Manhattan model, which corresponds to the distance range between nodes traveling on parallel roads. Smoothing the peaks out, MN comes very close to the MMTS model for this metric. The measurement results of the neighbor distance in the GIS model with traffic lights (GIS-F-T) show peaks at intervals of 5 meters which correspond to the distances between nodes queued in front of traffic lights.

## 4.6 Number of Neighbors

We measure the number of neighbors for each node which corresponds to the node degree in the network graph. Fig. 10 shows the cumulative distribution of neighbors for different mobility models in the Urban Scenario. Around 20 percent of the nodes have less than 15 neighbors regardless of the employed mobility model. While 80 percent of the nodes in

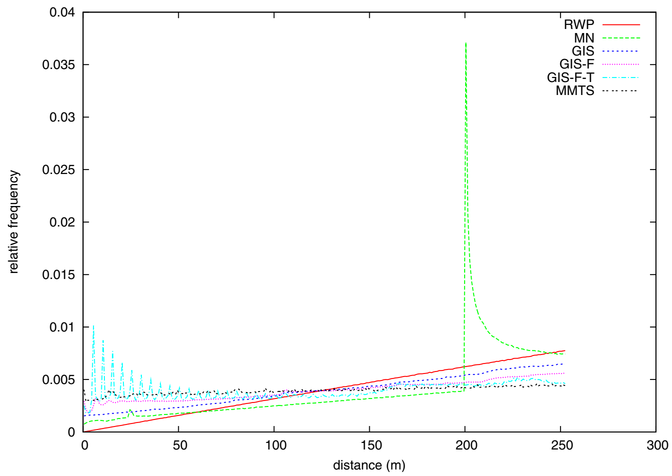



**Figure 8: Ratio of Distances Between Neighboring Nodes (Sampling Ratio is 1 Meter).**

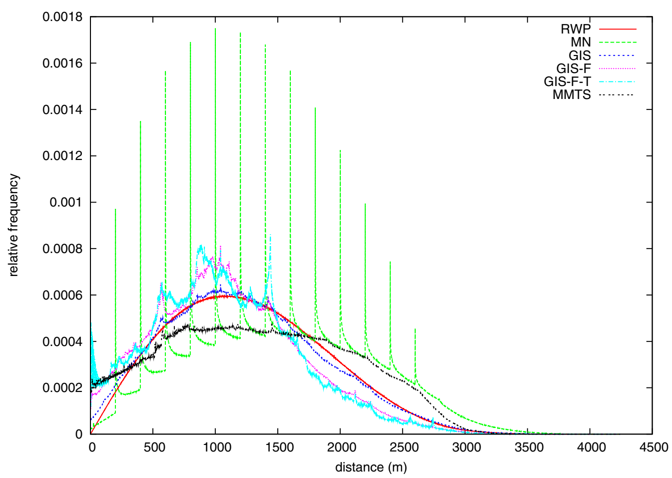



**Figure 9: Ratio of Distances Between All Nodes (Sampling Ratio is 1 Meter).**

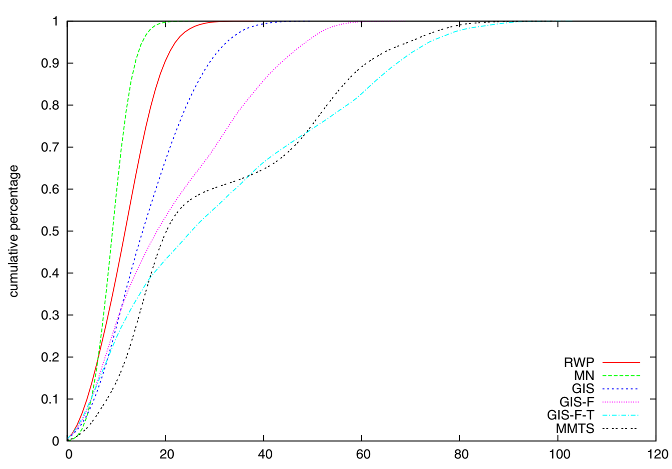



**Figure 10: Number of neighbors.**

the Random Waypoint model have less than 20 neighbors, 80 percent of the nodes in the MMTS model have less than 60 neighbors. We observe that the number of neighbors increases when car-following is enabled in the GIS model (GIS-F). Queuing in front of traffic lights (GIS-F-T) leads to clustering of nodes which increases the number of neighbors even more. As a result of this evaluation, we observe that the distribution of the number of neighbors in the GIS-F-T model approaches the realistic vehicular traces from MMTS.

## 4.7 Contact Duration

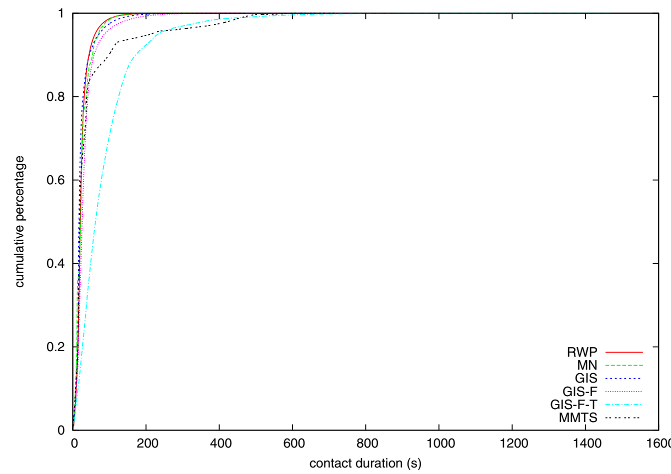



**Figure 11: Contact duration for nodes.**

The contact duration measures the time period during which two nodes are neighbors. The contact is lost when the distance between the two nodes exceeds the communication range. In Fig. 11, we observe that the cumulative distribution of the contact duration are similar for Random Waypoint, Manhattan, GIS and GIS-F. The traffic lights in the GIS-F-T model introduces queuing and, therefore, nodes have the same neighbors for a long time period due to the stop-and-go traffic phenomenon. Nodes move for a long time in close distance to each other due to the structure of the road network in the MMTS model.

## 4.8 Major Findings

Based on the previous analysis of the different mobility models, we draw the following conclusions.

First, realistic mobility models (GIS and MMTS) exhibit a high extent of similarity between the movements (speed, direction) of two nodes which are in close distance to each other. The Random Waypoint model clearly fails to mimic this realistic behavior of vehicles in road traffic scenarios.

Second, the restriction of node mobility to a highly realistic road topology in our GIS-based mobility models has a significant influence on the node density and on clustering of nodes at hot-spots (traffic lights, major roads). This effect can be observed to a similar extent in the realistic vehicular traces from the traffic simulator (MMTS). This clearly proves the high influence of micro-mobility on important metrics for networking.

Then, considering the MMTS traces as a benchmark model, we can draw several conclusions. First, it is interesting to note that for some metrics our GIS models and especially the GIS-F-T approaches very closely to the ideal model. On the other hand, the MN performs also very well for some metrics. This leads us to think that a tradeoff can be found between microscopic mobility models such as our GIS models which are hardly derivable and the Manhattan model which is analytically tractable. This and the previous finding confirm to some extent findings presented in [10] by Wang et al. .

The question is now to what extent the MMTS model can be used for network performance evaluation since only major roads are represented. The ITS community is only interested in traffic optimization and as such does not require to model traffic on less important roads. For networking, this is problematic since this vehicular traffic can allow inter-vehicular communications between cars taking different major axes. The impact on ad hoc networking and especially content dissemination is surely important.

# 5. CONCLUSION

In this paper, we have proposed GMSF – a Generic Mobility Simulation Framework –. GMSF implements classical mobility models (i.e., Random Waypoint, Manhattan) and new GIS-based models (i.e., GIS, GIS-F, and GIS-F-T). These latter use highly precise road maps, realistic speed limits, and incorporates the influence of other vehicles and traffic lights. GMSF also includes a realistic mobility model from the ITS community we consider as a benchmark model.

But more than proposing mobility models, GMSF is one of the first modular framework allowing the comparison of models. These comparisons will be more and more important in the future to generate and verify the accordance of new models with reality. In fact, the fully functional implementation of this framework greatly simplifies the generation of mobility traces and the evaluation of different mobility models with its wide choice of metrics. As a result of its modular design, the framework can be easily extended with additional functionality. As such, we consider GMSF to be a first step toward vehicular mobility benchmarking. Yet, due to the lack of real vehicular traces from measurement campaigns, it is difficult to benchmark how close our mobility model comes to reality. Therefore, we restrict our evaluation to a comparison of our new GIS mobility model with the Random Waypoint model, the Manhattan model and with vehicular traces from a traffic simulator (MMTS) that are considered highly realistic. This comparison reveals unexpected differences and our major findings are that (i) our GIS models come close to the MMTS model considered as a benchmark, (ii) microscopic behaviors have a high influence on designing realistic models, (iii) yet, classical models such as the Manhattan model does not perform so bad and a tradeoff between classical mobility models (analytically tractable) and microscopic mobility models (not tractable) is to be investigated, and (iv) more measurements are required to assess the validity of "synthetic" models.

We plan to further extend GMSF toward a full benchmarking framework with new mobility models but also real vehicular traces to assess the validity of models. GMSF along with its documentation is publicly available at: `http://gmsf.hypert.net`.

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# APPENDIX

# A. GIS GLOBAL BEHAVIOR

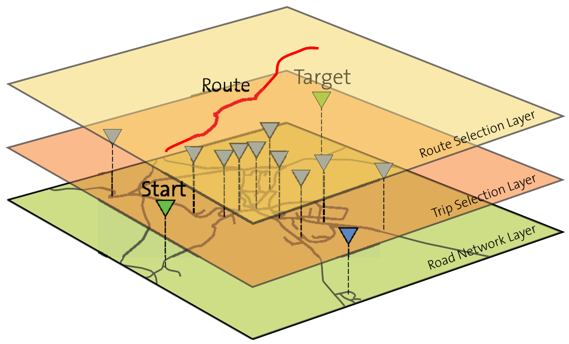
For the global behavior, a pre-trip rule enables vehicles to choose start and end point from a set of points of interests on the concerned area of the GIS map. This rule defines then the exact route for this trip. When arrived at destination, vehicles choose another end point for their trip and repeat this process until the simulation ends. An important factor influencing this rules is the formation of a consistent street network representation. For this, we extract a static street network database from the GIS maps. In this database, each street is considered as an edge valued proportionally to its length, its number of lanes, and its speed limit. Examples of implementations of the route choice behavior (i.e., pre-trip rule) is to perform a shortest or fastest path computation on this database. More details about these global and local rules and their implementation are shown in Fig. 12 and 13, respectively.

| Road Category | Speed Limit |
|---|---|
| 1, 2, 3, 4 | 33.33 m/s |
| 5, 6, 7 | 16.67 m/s |
| 8, 9 | 13.89 m/s |
| others | 8.34 m/s |

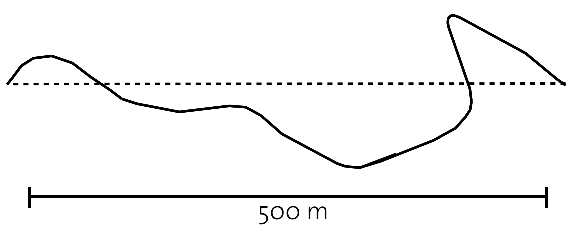
**Table 1: Speed limits for the different road categories in the GIS model.**

# B. GIS LOCAL BEHAVIORS

As for local behaviors, our GIS-based model implements speed adjustment and the car-following mechanism using the Intelligent-Driver Model (IDM) [16] on single lanes with bidirectional traffic. Additionally, major street intersections are controlled by a traffic light management scheme and a turning behavior.




(a) **From the static street network database to the route selection**. The pre-trip rule consists of modules operating at different layers. The *Road Network Layer* is the highly detailed street topology represented as a database. On top of this street topology, the *Trip Selection Layer* chooses a start and end point for trips from a set of points of interest. At last, the *Route Selection Layer* calculates the exact route for this trip (an example is given below. This latter task can be performed using different algorithms. The Shortest path algorithm sets the edge weight (costs) to the length of the street and executes Dijkstra's shortest path algorithm. The *Fastest path algorithm* sets the edge weight (costs) to the time it takes to pass through the street with the maximal allowed speed.

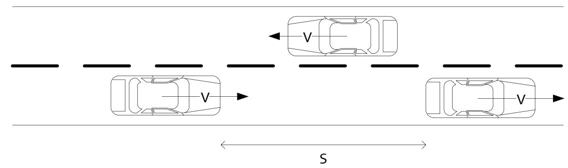



(b) **Example of a route trip's topology.** The topology of the street network is based on a highly detailed landscape model extracted from the GIS maps (cf. Fig. 3). A street is modeled as a collection of line segments following the exact course of the street rather than just connecting the start and end point of a street with a direct line. This figure shows an example of the detail level of the employed street data. Furthermore, a speed limit is assigned to each street section based on the street category. Table 1 gives the maximal speed for each different categories of streets found in the GIS maps.

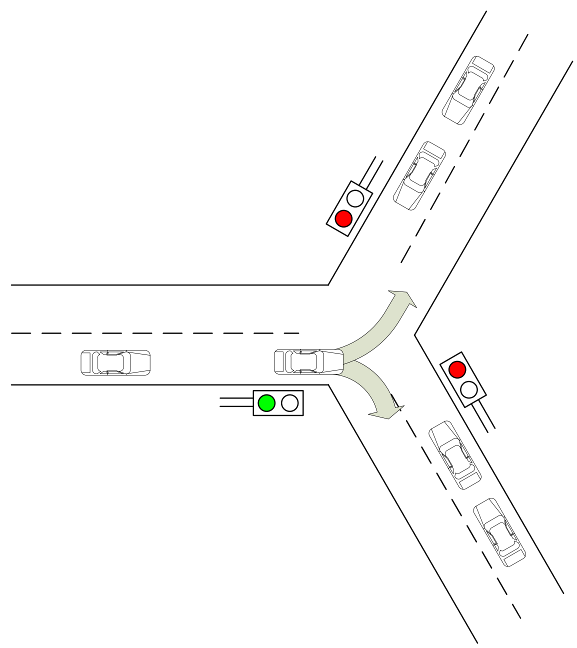
**Figure 12: Global behavioral rules in detail.**

| Parameter | Description | Value |
|---|---|---|
| $v_0$ | Desired speed | speed limit |
| $a$ | Acceleration constant | 0.6 |
| $b$ | Deceleration constant | 0.9 |
| $T$ | Reaction time | 0.5 s |
| $s_0$ | Minimal gap between vehicles | 1 m |

**Table 2: Local behavioral rules parameters.**




(a) **Basic Motion.** The speed of a vehicle in the next simulation step depends on the current speed $v$, the desired speed $v_0$, and on the distance to the front vehicle. The following equation defines the speed change for a vehicle between subsequent simulation steps: $\frac{dv}{dt} = a\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*}{s}\right)^2\right]$. A desired dynamical safety distance $s^*$ to the front vehicle is maintained which depends on the current speed, the speed difference to the front vehicle $\Delta v$, a driver's reaction time $T$ and the minimal acceptable distance between two vehicles $s_0$. Formally, $s^* = s_0 + \left(vT + \frac{v\Delta v}{2\sqrt{ab}}\right)$. The acceleration in the former Equation is divided into two parts: a "Free-road" term and a "Breaking" term. The Free-road term is used to accelerate the vehicle until the speed limit is reached. The Breaking term restricts the speed to maintain a safety distance to the front vehicle. When no vehicle is ahead, the Breaking term outputs zero. Table 2 below shows the parameter's numerical values used in these equations.



(b) **Intersection Management.** Currently, no information is available from the GIS data to determine which traffic rules apply at an intersection. Therefore, admission control to intersections is based on a set of simple rules. Less important intersections (small streets) are served by a first-come first-serve principle. The vehicle which has the smallest distance to the intersection is allowed to pass, other vehicles have to wait until the intersection is free. More important intersections are controlled by traffic lights. One street at a time has a green traffic light, all the others are red. Scheduling of the green phase is done using a round-robin algorithm where the duration of the green phase is set proportional to the street category.

**Figure 13: Local behavioral rules in detail.**