Evaluation of Mobility Models For Vehicular Ad-Hoc Network Simulations

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Abstract: There is a growing interest in deployment and evaluation of routing protocols for Vehicular Ad-Hoc Wireless Networks (VANETs) in urban contexts. The mobility model of nodes is one of the most important factors that impacts the evaluation of any wireless ad-hoc routing protocol using simulations. In this paper we make the case that the state-of-the-art simulation techniques do not effectively model many important factors that come into play in urban mobile environment. We present two new simple mobility models for VANETs that account for constrained movement pattern of vehicles on urban streets. Using traffic patterns and street maps, we perform a comprehensive comparison of the impact of our two new mobility models against two earlier mobility models. Unlike prior results in this area, our results demonstrate that the mobility model used in simulation does significantly impact the delivery ratio and packet delays in VANETs. With plenty of room for further improvement, our models provide a sound starting point for the development of more realistic and accurate mobility and obstacle models for VANET simulations.

Keywords: Mobility Model, Vehicular Ad-Hoc Network, Wireless Simulation

1 Introduction

There is a growing commercial and research interest in the development and deployment of Vehicular Ad-Hoc Networks (VANETs). VANETs are special applications of the more general Mobile Ad-Hoc Networks (MANETs) and consist of a set of vehicles traveling on urban streets and capable of communicating with each other without a fixed communication infrastructure. VANETs are expected to be of great benefit for safety applications, gathering and disseminating real-time traffic congestion and routing information, sharing of wireless channel for mobile applications etc.

Because of the high cost of deploying and testing any new VANET architecture in real world, simulations provide a vital alternative for conducting cheap and repeatable evaluations prior to actual deployment. The key simulation factor that impacts the performance of VANETs is the mobility pattern of vehicles, also called the *mobility model*. Mobility model determines the location of nodes in the topology at any given instant, which in turn directly impacts the network connectivity. The current mobility models, used in popular wireless simulators such as NS-2 [1], largely ignore real world artifacts such as street layout and traffic signs. As a result, the evaluation results are unlikely to be good predictors of protocol performance in the real world. For example, the traditional Random-Waypoint (RW) [8] model assumes that nodes can move around in an open field without obstructions in any direction. In contrast, vehicular movement in urban settings is constrained by the layout of roads, intersections with traffic signals, buildings, and other obstacles. Other recent efforts at modeling mobility [10, 7] do not consider factors specific to urban settings such as traffic signs, stop signs and queuing of vehicles at intersections.

In this paper, we provide initial answers to the research question of whether, and to what extent, the choice of vehicular mobility model effects the performance of routing protocols in VANETs. This paper presents a detailed evaluation of the impact of mobility models used in simulations on the performance of the VANET routing protocols. Our specific contributions are as follows:

1. We develop two mobility models – the Stop Sign Model (SSM) and the Traffic Sign Model (TSM) – that capture the vehicular mobility characteristics on urban streets such as stop signs, traffic signs and interdependent vehicular motion.
2. Using the AODV protocol, we perform a detailed performance comparison of the impact of TSM and SSM models against two earlier models – the Random-Waypoint Model (RWM) [8] and the Rice University Model (RUM) [10]. We evaluate these models based on parameters such as topology (real maps as well as controlled grids), vehicular speed, and the wait times at intersections.
3. Our TSM and SSM models bring out a *clustering effect* at the intersections which significantly impacts protocol performance. The state-of-the-art models do not capture this effect. We find that increasing the number of nodes or the maximum wait times at intersections leads to increased clustering effect. In turn, increased clustering leads to higher delivery ratios when neighboring intersections are within transmission range, and to lower delivery ratios when neighboring intersections are beyond each other's transmission range (due to large block sizes).

The rest of this paper is organized as follows. Section 2 discusses the factors that influence mobility in VANETs and presents details of our SSM and TSM mobility models. Section 3 provides a detailed analysis of the results obtained in our performance evaluations. Section 4 reviews related research and Section 5 concludes with a summary of our major research contributions and future research directions.

2 Urban Vehicular Mobility Model

Mobility pattern of nodes in a VANET directly stresses the route discovery, maintenance, reconstruction, consistency and caching mechanisms. At any point in time, a VANET can have of a combination of both static and dynamic nodes. The static nodes tend to have a stabilizing influence on topology and routing by relaying the packets to/from the neighboring nodes. On the other hand, dynamic nodes add entropy to the system by causing frequent route setups, teardowns, and packet losses. In this section, we first identify the factors that influence the mobility in VANETS. Next we describe two new mobility models – the Stop Sign Model and the Traffic Sign Model.

2.1 Factors Affecting Mobility in VANETS

Layout of Streets: Streets force nodes to confine their movements to well defined paths irrespective of their final destination. This constrained movement pattern largely determines the distribution of nodes and connectivity of the network. Streets can single or multiple lanes and can allow either one-way or two-way traffic. We consider single-lane two-way streets in our initial models in this paper.

Traffic Control Mechanisms: The most common traffic control mechanisms at intersections are the stop signs and traffic lights. These mechanisms result in formation of clusters and queues of vehicles at the intersections, and reduces their average speed of movement. Reduced mobility implies more static nodes and slower rate of route changes in the network. Besides reducing mobility, cluster formation also affects network performance by increasing contention for the wireless channel. As we later show in Section 3, vehicle cluster formation at intersections can significantly impact network performance. We approximate two traffic control mechanisms in our initial models – stop signs and traffic signs.

Interdependent Vehicular Motion: Movement of every vehicle is guided to a large extent by the movement of other vehicles surrounding it. For example, a vehicle would maintain a minimum distance from the one in front of it, increase or decrease its speed, and may change to another lane to avoid congestion. In our initial single-lane models, vehicles travel within 5 miles/hour of the posted speed limit on each road, but do not overtake (or overrun) any vehicle in front.

Speed Limit: The speed of the vehicle decides how quickly or how slowly the vehicle's position changes, which in turn determines how quickly the network topology changes. Thus speed limit on a road directly affects how often the existing routes are broken or new routes are established. In our evaluations, we derive out speed limits from real map layouts in the TIGER database [2] maintained by US Census Bureau.

Block Size: A city block can be considered as the smallest area surrounded by streets, usually containing several buildings. Over an area comprising many blocks, the size of block plays an important role in vehicular communication pattern. The block size determines the number of intersections in the area which in turn determines the frequency with which a vehicle stops. It also determines whether nodes at neighboring intersections can hear each other's radio transmission. In our simulations, we study various block sizes for grid topology and typical block sizes from the TIGER database for real maps.

2.2 Stop Sign Model (SSM)

In the Stop Sign Model (SSM), every intersection has a stop sign, such that any vehicle approaching the intersection must stop at the signal for a fixed waiting period. Each vehicle's motion is governed by the vehicle in front of it. This is quite intuitive – a vehicle moving on a road can never move further than the vehicle that is moving in front of it, unless it is a multi-lane road and the vehicles are allowed to overtake each other. Throughout this paper, we assume that all roads have a single lane and that no vehicles are allowed to pass each other. (Extending our model to multiple lanes is the next logical step.) When vehicles follow each other to a stop sign signs, they form a queue at the intersections. When a vehicle reaches the front of the queue it waits for a fixed amount of time before crossing the intersection. Although it is unlikely that an urban layout will have stop signs at every intersection, this model serves as a simple first step to understand the dynamics of mobility and its impact on routing performance.

2.3 Traffic Sign Model (TSM)

Next, we refine SSM further by replacing stop signs by traffic signals at intersections. In general, vehicles need to stop only at the signals that are red and drive through the signals that are green. While it is possible to very accurately simulate the operation of each traffic light at every intersection, this would lead us to compute unnecessary details (and the associated state information) that do not significantly affect routing protocol performance. Instead, we focus on factors that influence routing protocols by approximating the operation of traffic signs as follows.

When a node approaches an intersection and finds itself at the head of the queue at the intersection, it decides with a probability p whether to stop (or with $(1 - p)$ to cross the signal). If it decides to wait, the amount of wait time is randomly chosen up to a maximum value w. Any node that follows while the first node is still waiting at the queue will have to wait for the remaining wait time plus one second (to simulate the delay in starting of queued cars). Whenever the signal turns green, the vehicles begin to cross the signal one after the other at intervals of one second, until the queue is empty. The next vehicle that arrives at the head of the queue again makes a decision on whether to stop with a probability p and so on.

3 Performance Evaluation

In this section we present the results of our experiments to analyze and compare the impact of various mobility models on routing protocol performance. We conducted experiments using the wireless network simulator NS2 [1]. Table 1 presents a summary of the values of various parameters used in our NS2 wireless simulations, except in experiments where a parameter itself is varied. We implemented the Stop Sign Model (SSM) and Traffic Sign Model (TSM) in C++ as independent programs that generated files with mobility patterns which could in turn be used as input to the NS2 simulator. Initial node positions and their destinations are chosen randomly. Each node follows the shortest path through the roads to its destinations and, upon reaching a destination, the node begins journey to another random destination along the shortest path. We compared SSM and TSM with the Random Waypoint Model (RWM) [8] and the Rice University Model (RUM) [10]. The RWM models simulates mobility in a open field where there are no no obstacles, roads or intersections. The RUM models roads in a real map, but the vehicles do not stop at intersections.

For controlled experiments, we performed the evaluations with a grid topology over a 1200 × 1200 square meter area, with blocks of varying size. We also performed experiments using several real world street maps using the information from US Census Bureau TIGER [2] database. Although real world maps are useful in understanding marco-level behavior mobility models, we primarily rely on the more controllable grid topology to understand fine-grained workings of these models. To conduct the large number of experiments required in this study, we used a 15 node cluster of machines running on the Unix platform to run the experiments in parallel and thus speed up the data collection process. Each experiment was repeated with multiple mobility patterns to attain a 95 % confidence interval.

3.1 Variation with number of nodes

In this section we compare the performance of different mobility models as we vary the number of total nodes. in a $1200m \times 1200m$ grid topology with block

Parameter	Value(s)
Number of Nodes	100
Simulation Time	900 sec (excluding 450 sec warmup)
Routing Protocol	AODV
NS2 Version	ns 2.28
Transmission Range	250m
CBR Sources	15 sources (4 pkt/sec,64 byte pkt)
Mobility Models	RWM, RUM, TSM, SSM
Topologies	1200X1200m Grid with 200mX50m block size, Real Map
Maximum Wait Time	SSM–3 sec, TSM–30 sec ($p = 0.5$)
Average Node Speed	15 meters/sec
Performance Metrics	Delivery Ratio, End to End delay, Mobility, Clustering

Table 1. NS2 Wireless Simulation Parameters

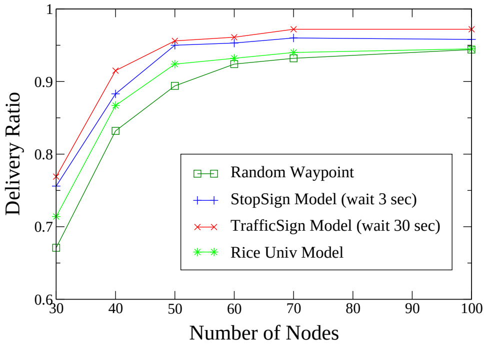

Fig. 1. Variation of delivery ratio with number of simulated nodes. This graph presents the relative performance of all the evaluated models. It may be noted that the graph axis was truncated to highlight the differences between the performance of the mobility models.

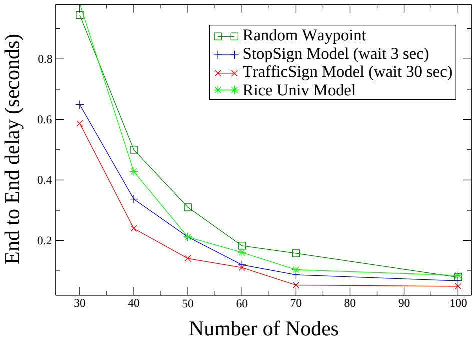

Fig. 2. Variation of end to end delay with number of simulated nodes TSM results in the best performance, and the delay value decreases as the number of nodes is increased, but eventually levels out at a constant level.

size of $200m \times 50m$. Figures 1 and 2 compare the delivery ratio and end-to-end delay among all mobility models.

The results indicate that the RWM yields the lowest delivery ratio and the maximum end to end delay. The RUM follows the RWM closely – in fact the performance with the two models is indistinguishable for 100 nodes and beyond. The SSM yields the next best delivery ratio and end-to-end delay. The TSM is observed to yield the highest delivery ratio with the smallest end-to end delay.

Across all mobility models, the common trend is that the delivery ratio increases with the number of nodes. Similarly, the end-to-end delay decreases as the number of nodes increases. This is because increasing the number of nodes leads to better connectivity in the network and better delivery ratio. In the rest of the experiments, we use 100 nodes for simulations.

3.2 Variation with number of CBR Sources

In this section, we present the variation in delivery ratio and packet delay with the number of Constant Bit Rate (CBR) sources in a $1200m \times 1200m$ grid topology with block size of $200m \times 50m$ and 100 nodes. Figures 3 and 4 show that as the number of sources increases beyond 15, there is a significant drop in

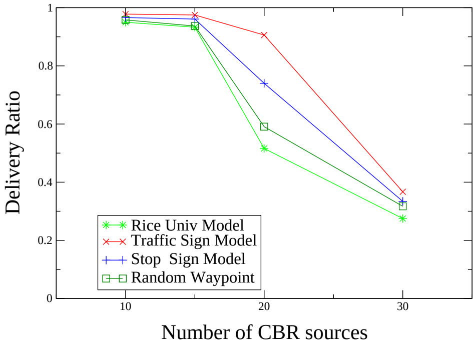

Fig. 3. Variation of delivery ratio with number of CBR sources. The delivery ratio increases as we increase the number of sources to 15, but any further increase leads to a rapid drop as the channel contention in the network increases. Among all the three models, TSM is seen to result in the highest delivery ratio, followed by SSM and RUM.

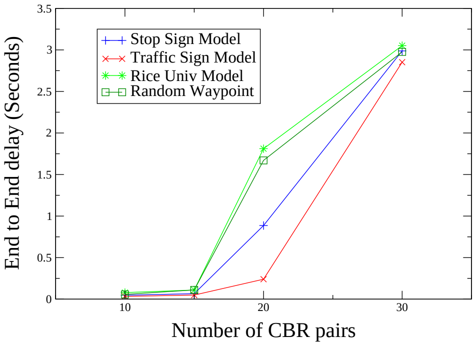

Fig. 4. Variation of end to end delay with number of CBR sources. The trend seen here is similar to the results for delivery ratio, with a rapid increase in end to end delay as the number of sources is increased beyond 15. As with delivery ratio, TSM results in the lowest end to end delays among all evaluated models.

the delivery ratio and a corresponding increase in the end-to-end delay. As the number of CBR sources increases, there is an increase in the number of packets contending for a common wireless channel, which leads to more collisions and packet drops. For the remaining experiments, we use 15 CBR sources among a total of 100 simulated nodes.

3.3 Variation with Vehicle speed

Since speed of the vehicles is a significant aspect of any mobility model, we varied the maximum speed for the vehicles and analyzed the resulting performance of various mobility models. Figure 5 shows the results of this experiment. It should be pointed out here that the maximum speed by default is based on the type of road, as defined by the Census Bureau. We varied the speed from its default value to study the impact of this parameter on the resultant mobility pattern. The results show a significant drop in the value of the delivery ratio for RUM as speed is increased. RUM represents a network with highly dynamic topology in which vehicles constantly move through the streets without stopping at any intersection. This results in a continuous churn in routes between different sources and destinations. The delivery ratio of the SSM (with a wait time 3 sec) also decreases with the increasing maximum speed, but not to the extent it does with RUM. The performance of TSM (with a maximum wait time 30 sec) does not vary much with the increasing maximum speed. The results for TSM and SSM are explained by the fact that these models effectively make the traffic less mobile due to the wait times at intersections. Since the vehicles spend a significant amount of time in waiting at intersections, higher speed does not change the network topology as rapidly as with RUM and routes have a higher degree of stability and lower churn rate.

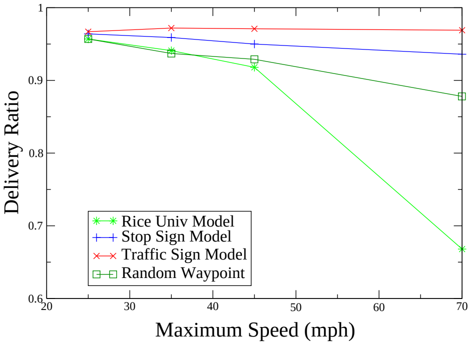

Fig. 5. Variation of delivery ratio with maximum speed of vehicles. As the speed increases the delivery ratio drops. This decrease is most significant for the RUM model, as compared to SSM and TSM which are not as mobile networks.

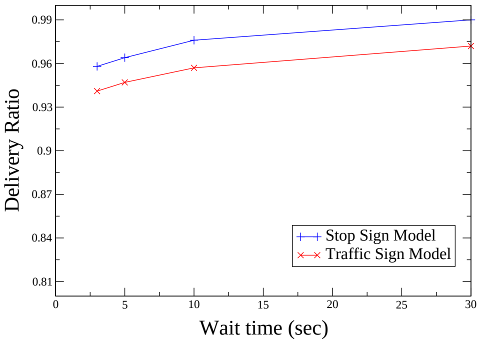

Fig. 6. Variation of delivery ratio with maximum wait time at intersections. For the same wait time Stop Sign model is less mobile as compared to the Traffic Sign model, and displays a higher delivery ratio

3.4 Variation with maximum wait time at intersections

To further understand the impact of vehicles stopping at intersections, we varied another important parameter – the maximum wait time of nodes at intersections. Figure 6 plots the packet delivery ratio as the value of maximum wait times at intersections is varied. The results bring out an interesting aspect of this study. As expected, the RUM model yields the lowest delivery ratio due to its highly dynamic pattern of the mobility. However, in contrast to our earlier experiments, the SSM is seen to yield a higher delivery ratio as compared to the TSM for the same values of wait times. The reason why SSM delivers better performance over TSM for a given wait time is that the SSM models a more static network than TSM where every node is forced to stop at each signal. On the other hand, nodes at the head of queue in TSM decide with a 50% probability whether or not to wait and, in the latter case, how long to wait. Thus TSM represents a more dynamic network than SSM.

The apparent contrast with our earlier experiments can be understood by noting that we used a larger value of maximum wait time (30 seconds) for TSM than what was used for SSM (3 seconds) i.e. TSM is modeled as a more static network than SSM in rest of the experiments which results in a higher delivery ratios for TSM. This models the real-world observation that the waittime at a traffic signal tends to be much larger than that at a stop sign.

3.5 Effect of Block Sizes

The block sizes in the topology play an important role in determining the performance of the routing protocol. Given larger block sizes, vehicles spend a relatively longer time in traversing the distance between intersections; thus they are mobile for a longer time. This increased mobility would lead to a weakened connectivity in the network, and a corresponding drop in the delivery ratio. To validate this we performed experiments where we varied the block size in a 1200mX1200m grid. The results in Figure 7 validate our observation above - as the block size

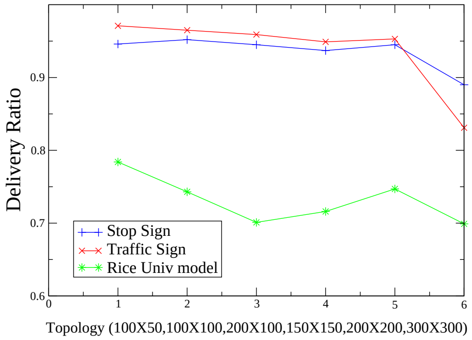

Fig. 7. Variation of delivery ratio with increase in block size. The variation in performance with change in the topology is evident from the graph.

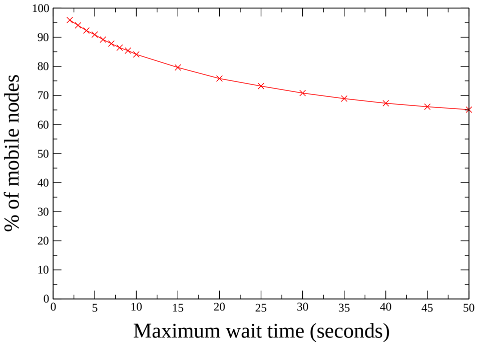

Fig. 8. Variation of fraction of mobile nodes with wait time in the Traffic Sign Model.

increases, the delivery ratio is indeed found to decrease. In fact, over the largest evaluated block, SSM is found to yield in an improved performance over TSM due to lower churn rate of routes, illustrating the significance of block sizes in the VANET simulation.

3.6 Analysis of The Impact of Increased Mobility

The results of our experiments so far clearly displays the trend that the performance of the SSM is better than the RUM, and TSM performs the best out of all evaluated mobility models. This brings into context our hypothesis that the varying degree of mobility within these networks is the reason for differing performance. The SSM performs better than the RUM due to the queuing of vehicles at intersections introduced within this model. TSM performs even better since it results in a network that is even more static. In SSM, each node is forced to stop at each intersection. On the other hand, in TSM, they stop only at some of the intersections and queued nodes crossing a traffic signal do so one behind another analogous to the manner in which traffic proceeds when a traffic signal turns green. On the other hand, the wait times for TSM are intuitively higher as compared to SSM. This leads to a network that is effectively more static when compared to SSM. This explains the improved connectivity in the TSM and the corresponding the performance improvements.

To gain a further insight into the behavior of the mobility models and the impact of the mobility on the performance of the entire network, we analyze the mobility traces in order to devise metrics that could explain this behavior. We observe that the metrics that could help to explain the results would need to be a direct measure of the mobility of the nodes and the clustering of vehicles on intersections. Thus the first metric we analyze is the average fraction of mobile nodes in the network at any time. This metric provides us a measure of the number of nodes we expect to actually be mobile at any given instant. The second metric we analyze is the extent of clustering at intersections. The number of vehicle clusters can be treated as an effective number of nodes in the network, since all the nodes in a cluster display similar connectivity to nodes outside the cluster.

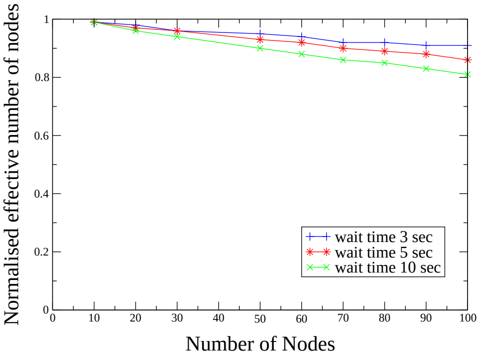

Fig. 9. Variation in the number of clusters (as a ratio of the total number of nodes) for SSM.

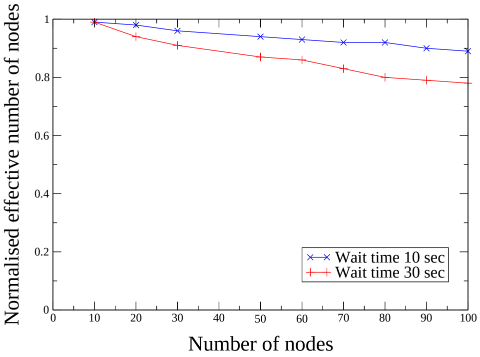

Fig. 10. Variation in the number of clusters (as a ratio of the total number of nodes) for TSM.

3.6.1 Average number of mobile nodes

To compute the average number of mobile nodes we computed the number of nodes waiting at any intersection, and averaged this over each second of the simulated time. Figure 8 presents the plot obtained from this experiment for the TSM. We observe that an increase in the wait time results in a decrease in the average number of mobile nodes. At a value of 2 seconds, the network is almost perfectly mobile, but as the waittime is increased the mobility in the network decreases gradually. This validates our intuition that the maximum wait time is a critical parameter that directly effects the level of mobility and, consequently, churn in the routing state.

To study the effect of topology on mobility, we also varied the block sizes across these experiments. The figures are excluded for space constraints. To summarize the results, for the 1200X1200 grid the larger block size results in increased mobility since the nodes now spend more time in traversing the longer roads between the intersections. A smaller block size results in reduced mobility since now the nodes spend more time waiting at intersections as compared to the time spent in traversing the relatively shorter roads between intersections.

These trends are observed for both the stop sign and traffic sign models. Under similar conditions of wait time and topology, the stop sign model is less mobile when compared to the traffic sign model. However an interesting observation from our experiments is that, for the same wait time, an increase in the number of nodes does not appear to affect the average number of mobile nodes significantly. This implies that the topology and wait time are more significant factors as compared to the number of nodes, unless we have sufficiently high number of senders to saturate the wireless channel with collisions.

3.6.2 Average Number of Clusters

The net effect of the stopping of nodes at intersections is that effectively many clusters are created all over the network. Connectivity among the nodes within a cluster is almost perfect. On the other hand, if one node in the cluster is unreachable for a certain node outside the cluster, then most likely all nodes in the cluster are unreachable for that node. The number of such clusters can be treated as the effective number of (logical) nodes in the VANET at any time.

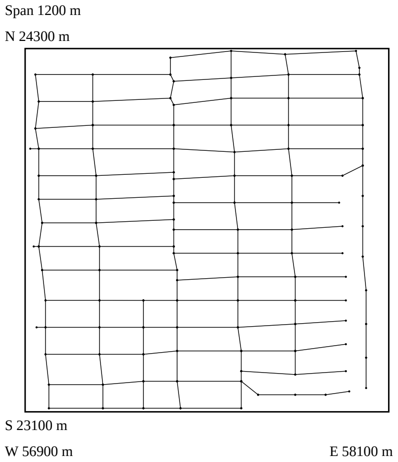

Fig. 11. Real world map - 1200 X 1200m Map extracted using the information from TIGER database. All lines represent actual roads within the plotted area.

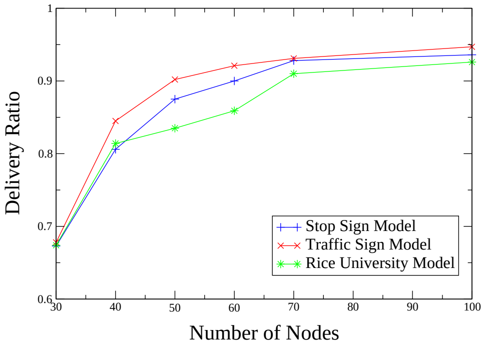

Fig. 12. Delivery ratio variation over total number of nodes. Experiment performed over a real map extracted using the TIGER database. The map used was a residential area with smaller block sizes. Results found to be similar to the earlier trend observed with the grid topology

To get an approximate estimate of the number of clusters, we divide the entire area into smaller regions and compute the number of nodes in each of these regions. Figures 9 and 10 present the highlights for this analysis for SSM and TSM. The figures show that as the total number of nodes increases the number of clusters increases, thus indicating that nodes are increasingly lined up on intersections waiting for their turn to move onwards. A similar effect is observed with an increase in the maximum wait time.

3.7 Real Map Results

Having obtained an insight into the various factors affecting the VANET in a uniform grid topology, we conducted experiments using real maps obtained using the TIGER database. We performed a set of experiments using a smaller section of the map used by RUM[10]. The original map was 2400 × 2400m, but the simulations at this size did not scale due to the large number of nodes (or conversely, unrealistic transmission ranges) required to maintain meaningful delivery ratios. To address this problem, RUM[10] had increased the nodes' transmission range from the default 250 meters in NS-2 to 500 meters. However, we felt that 500 meters was way too large a transmission range for the the VANETS that we were considering. Hence we selected a much lower value of 250 meters as the transmission range, and to maintain manageable simulations, truncated the map size to 1200 × 1200.

Figure 11 displays the layout of the map used for this particular set of experiments. The results of these experiments are summarized in Fig 12. These results are again found to follow the trend that we observe in our earlier experiments using the grid topology. The TSM presents the highest delivery ratio with the least end to end delay, and the SSM and the RUM follow in that order. This effectively validates our hypothesis regarding the correlation between topology and mobility, and between the mobility and performance of the network.

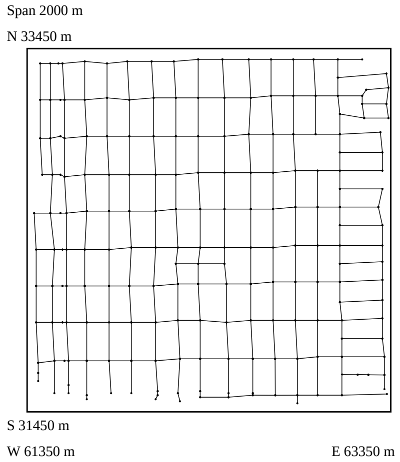

Fig. 13. Real world map - 2000 X 2000m Map. Leon County .

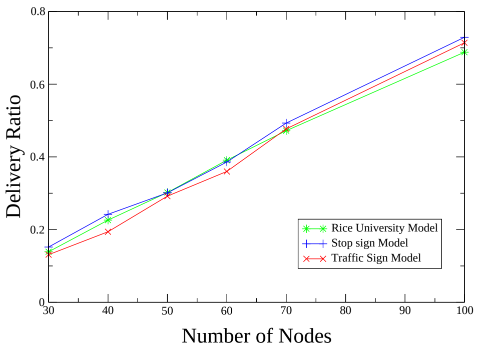

Fig. 14. Delivery ratio variation over total number of nodes. No definate pattern observed here, due to the fact the this is a bigger map, and the number of nodes is not high enough

As another experiment, we extracted a map of Leon county, over an area of 2000 X 2000m, and carried out a complete set of experiments over the map. The results in this case were differant from what we had seen so far. Figures 13 and 14 present the actual map and the graph showing the variation in delivery ratio as the number of nodes was increased.

In this instance, due to the higher pause involved in the traffic sign model, once a node is in the waiting state at an intersection, it is highly likely that it would not be able to communicate with other nodes waiting on other intersections due to the large size of the map. This particular topology is quite regular, but due to the fact that this is over a larger area the results present a differant trend. This again brings into perspective our observation that the topology plays a significant role in determining how such mobility models perform.

4 Related Work

The traditionally used mobility models is the Random WayPoint model [8]. Some of the other similar open-field models are the Random Walk, Random Direction Model and the Boundless Simulation Area model [4]. These models possess a large degree of randomness, in terms of the direction/destination of travel of the nodes. from a given range of minimum and maximum speed distribution. Camp et al [4] mention that the node concentration or the node spatial distribution in these models is towards the center of the simulation area as the simulation progresses. The nodes appear to converge and diverge repeatedly at the center, a behavior that leads to inherent flaws in simulations using such models.

Davies [6] presents a comprehensive evaluation of existing mobility models for ad-hoc networks. They noted that none of the evaluated models depict realistic mobility scenarios and there is a need to implement mobility models appropriate for scenarios under consideration. [13] reached a similar conclusion after evaluating many of the more recent mobility models. Yoon et. al [11] highlight the fact that RWM simulations can give erroneous results due to the failure of the model to achieve a steady average node speed.

Previous works have attempted to improve upon RWM to make it more realistic. [3] attempts to model the acceleration/deceleration in vehicles, to improve the realism in RWM. The random trip model [9] was proposed as a generic model that contains other mobility models, including RWM. Authors attempt to increase the realism in the mobility model by producing a perfect sample of the initial state for a random trip model. In [12] the authors claim that in most mobility models the average speed decays over time before reaching a steady state value. They point out that this can lead to erroneous results in simulations that rely on results averaged over time, and present a framework to eliminate this problem. Jardosh et al. [7] introduced obstacles in the simulation area to constrain mobility as well as wireless transmission. Their model explores communication on college campuses where nodes tend to move through obstacles, congregate at attraction points or choose destinations decisively. The placement of obstacles guides the computation of paths using Voronoi diagrams, which may not be entirely realistic in a VANET environment.

Most of the above mentioned research targets mobility modeling in general, but not much work has been done towards mobility modeling specifically for VANETs. Models such as the Random Waypoint Model involve movement of nodes in an open free space, which is not the case in VANETs which involve vehicular motion restricted to streets and under specific rules. Saha et al [10] modeled mobility for vehicular ad-hoc networks on real street maps obtained from TIGER database [2] maintained by the Census Bureau, by constraining vehicle mobility to street boundaries. Their model, which we call the Rice University Model (RUM) in this paper, does not enforce any specific traffic rules on the network, especially at intersections. Authors observed in their study that the model resulted in results similar to the Random Waypoint model. Our paper validates that RUM indeed close resembles the RWM.

A recent work that is closely related to our study is [5]. In this project, a vehicular mobility model for urban environments was introduced and its performance was analyzed. However their results do not explore the effect of node clustering at intersections and its relationship to mobility in the manner we do in our work. Additionally, we believe that the evaluation parameters used in their work lead to low delivery ratios that are not useful in real-world VANETs.

5 Conclusions

In this paper we have argued that mobility models play a key role in affecting the performance of routing protocols in Vehicular Ad-Hoc networks (VANETs). We presented an in-depth evaluation of important factors that impact the performance of VANETs with different mobility models. We proposed two new but related vehicular mobility models – the Stop Sign Model (SSM) and the Traffic Sign Model (TSM) – that approximate the movement pattern of vehicles in urban environments to different degrees. To the best of our knowledge, ours is the first work that analyzes the impact of clustering and its effect on node mobility and protocol performance in ad-hoc networks. We observe that the performance of such a network is highly dependent on certain factors that includes the topology, and the time that nodes spend waiting at intersections. This work is a beginning step towards developing an understanding of the various factors that are required to correctly simulate vehicular mobility models. We plan to build upon the TSM to include further details such as coordinated crossings at intersections from different directions, one-way streets, multiple lanes and signal attenuation due to obstacles. Our goal is to develop the TSM model to a stage where simulations of vehicular MANETs can be assumed to reliably reflect the behavior when such a network is physically deployed.

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