Opportunistic Vehicular Networking: Large-Scale Bus Movement Traces as base for Network Analysis

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***Abstract*—In many road traffic scenarios the ability to communicate among traffic participants is very helpful. Therefore, research and development in academia and industry in that field exists already for many years and is ongoing in several directions. Some examples are Vehicular Ad-hoc Networks (VANETs), e.g., using technologies like IEEE 802.11p, and vehicles communicating with backend systems, e.g., using 2/3/4G cellular networks.**

In opportunistic vehicular networks, vehicles may not only exchange data for the immediate use such as Cooperative Awareness Messages (CAMs) in the ETSI Intelligent Transport Systems (ITS). Instead, a more general type of network might be set up, also for application scenarios beyond direct road traffic related aspects. For instance, buses of public transportation systems could collect data from the field or distribute data among several buses. Thus, buses could become an important part of smart cities or Internet of Things (IoT) application scenarios.

Important questions are then, e.g., how much data could be distributed in such a bus-based opportunistic network or how often is it possible to exchange data between buses. Usually, buses in urban public transport systems follow well planned but nevertheless highly dynamic schedules and trajectories. Thus, traffic conditions have a significant and complex influence on bus mobility, causing very characteristic movement properties that are considerably distinct from other road vehicles. Understanding these special characteristics is essential for the design and evaluation of opportunistic vehicular communication networks. For this purpose we inspect two large-scale bus movement traces and describe the available data and metadata. Moreover, we analyze and compare vehicle density, speed, update intervals, and characteristics that are specific to public transport.

Especially for large cities, but even for smaller ones if many devices like vehicles, sensors, and various other IoT things are part of such a network, high-performance computing and simulation approaches are necessary to study, analyse, design, use and maintain such a system.

***Keywords*—VANET, Vehicular Networking, Opportunistic Networking, Movement Traces, Urban Public Transport, Delay Tolerant Networks**

I. Introduction

The ability to communicate is very helpful in many road traffic scenarios. Therefore, research and development in academia and industry in that field exists already for many years and is ongoing in several directions. Some examples are Vehicular Ad-hoc Networks (VANETs) [1, 2] , e.g., using technologies like IEEE 802.11p, and vehicles communicating with backend systems, e.g., using 2/3/4G cellular networks.

In opportunistic vehicular networks, vehicles may not only exchange data for the immediate use such as Cooperative Awareness Messages (CAMs) in the ETSI Intelligent Transport Systems (ITS)[3]. Instead, a more general type of network might be set up [4], also for application scenarios beyond direct road traffic related aspects. For instance, buses of public transportation systems could collect data from the field or distribute data among several buses. Thus, buses could become an important part of smart cities or of Internet of Things (IoT) application scenarios where they collect data from such devices and deliver this later on to some central system for further processing and decision making. An example could be a system where air quality sensors are deployed in the city and also on buses [5, 6] as illustrated in Figure 1. The values measured by these sensors can be collected by buses, exchanged with other buses, and finally be forwarded via gateways to central systems where they can be processed. Depending on the detected air quality, decisions like speed limits can be made and according command and control information be given to road signals.

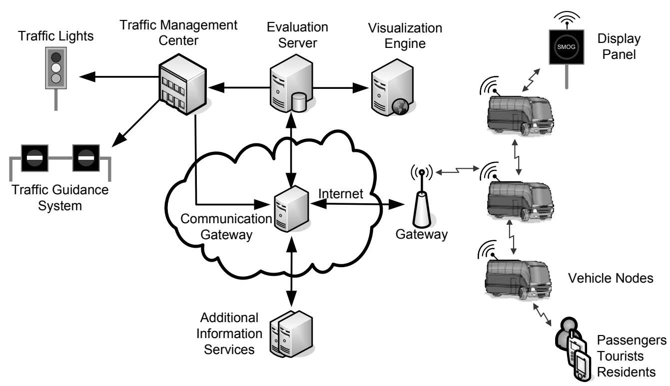

Figure 1. Environmental Monitoring in Metropolitan Areas.

But also for direct purposes of the transportation systems (as already indicated in Figure 1) communication systems can be helpful. They may increase the efficiency and the user-friendliness of urban public transport by improving dispatching, traffic management and dynamic rerouting. This causes a growing demand of vehicular communication services. Instead of using cellular networks with a high range but low in comparison data rates, there is a trend to using license exempt technologies such as IEEE 802.11a/b/g/n/p. However, these technologies usually have a shorter range, so that the communication system design is often based on ad-hoc or delay tolerant networking.

Here we focus on bus-based public transport in contrast to rail-based public transport for two reasons. First, buses are more widespread and more flexible than rail vehicles. And second, rail-based transport requires much more infrastructure investments, so that the additional cost for communication infrastructure (e.g. track-side units) is relatively low. This means that the potential of ad-hoc networking is higher in bus-based public transport, but also harder to design because mobility prediction is more uncertain. Therefore, an analysis of real public transport movement traces is essential for the design and evaluation of such systems. The authors of [7], for example, recommend considering buses for mesh network simulations. Vehicular and disruption-tolerant routing protocols [8, 9] also require real bus movement traces for development and evaluation. Moreover, real traces yield unexpected special characteristics in real-world scenarios, e.g. different situation-dependent distributions of contact duration in vehicular networks [10].

Unfortunately, publicly available large scale traces of entire public transport systems are very rare. There are traces of wireless connectivity available, e.g. [11], which contains timestamps and identifiers of devices within radio range of sensor nodes mounted to buses. However, the trace lacks position information of the buses, and is therefore not suited to derive general knowledge on the movement behavior of vehicles. There is also a trace of connectivity and vehicle positions [12, 13], but it comprises only 30-40 vehicles. Such small scale traces are useful for an analysis of contacts, but in order to understand the dynamics of vehicle movement and to conduct realistic simulations, large-scale traces are required. As far as we know, there are basically two trace sets of large bus-based public transport systems available. First, there is a mobility trace [14] of roughly 1200 buses in the Seattle area. The second is a trace [15] of more than 1600 buses operating in and around Chicago.

Realistic movement patterns (i.e. based on real vehicle movement in a real public transport network) are important for thorough studies of algorithms to be applied in public transport networks in general and especially for pre-deployment simulations. Using mobility models or synthetic traces for such purposes is a less-than-ideal solution, because the models and their parameters do not necessarily represent the complex real-world behavior of urban transportation systems. Therefore, certain real-world characteristics might be left out of consideration, which reduces the reliability of pre-deployment simulations based on non-real-world vehicle movement. However, reliable simulation results are very important in the development and validation process of vehicular communication systems, because they help to identify and eliminate problems before the cost-intensive field test or rollout phase.

In this paper, we analyze real-world traces, and point out trace-specific as well as common characteristics, and special properties of public transportation networks. We start with vehicle position update rates, amount of active vehicles and the distribution of their speed. Then the influence of rush hours and the spatial vehicle density is analyzed. We continue by pointing out operational properties such as vehicle-to-line assignment and inter-arrival times at stops. These characteristics are needed to understand the transport networks' dynamics, which have a significant influence on DTN and MANET connectivity and capacity. Exemplary areas of research that benefit from the knowledge of these properties are DTN and MANET routing and quality of service, as well as the development and evaluation of applications such as on-board monitoring, on-board passenger information systems, and content distribution to dynamic displays at the stops.

The remainder of this paper is structured as follows. In section 2 the large-scale Seattle and Chicago traces and their properties are introduced and described. Section 3 gives a detailed analysis of the mobility characteristics. For this purpose the amount and distribution of position updates and active vehicles is analyzed. We continue with an analysis of vehicle-to-line dispatching and vehicle density. In section 4 the paper is concluded by a discussion of similarities and differences of both traces.

II. Large-scale Bus Movement Traces

A. Seattle Trace

A trace [14] of roughly 1200 buses on 240 routes of the King County bus system was recorded in 2001 [16] and is available at the Crawdad (http://crawdad.cs.dartmouth.edu/) repository. The area around Seattle in which the buses are active is roughly 90 by 60 kilometers. Buses' positions are calculated by on-board Automatic Vehicle Location (AVL) systems. At the time that the trace was recorded AVLs installed in 1992 were in operation. These AVLs did not use GPS but a combination of signpost transmitters, odometry and mapmatching [17, 18]. Signpost-based AVLs combined with odometry provide an accuracy of 1-20m [19], which is potentially better than GPS. The drawback is that these systems only track vehicles on fixed routes. This means that it is not possible to track off-route vehicles. Location updates of on-route vehicles are "polled irregularly but approximately every minute"[17] and the samples are "70% 12 minutes or less apart and 90% 20 minutes or less apart"[16].

The trace that is publicly available at Crawdad is not raw but already processed. According to the 'readme'-file[14] it contains timestamps, bus identifier, route identifier and coordinates. There is also a field that is specified as 'unknown'. Moreover, the coordinates "are in feet and were computed from the latitude and longitude values reported in the raw traces"[14], which are to the best of our knowledge not publicly available. There is also no additional metadata such as route definitions, stop positions and timetables available for the Seattle trace.

Figure 2 shows 10000 consecutive position updates from the Seattle trace. Each dot represents one data point. Routes are clearly visible because of the large amount of samples plotted into the diagram. For visual comparison figure 3 shows a map (from Openstreetmaps) of the Seattle area. Note that Mercer Island is a good reference point. It is clearly discernible in figure 2 around coordinates (40000,20000). The transformation and

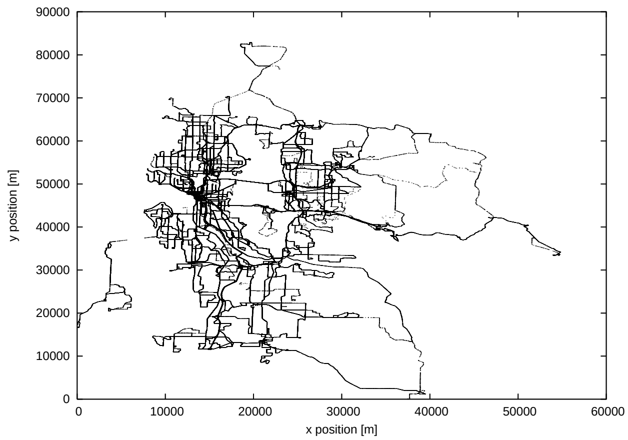

Figure 2. Position updates of the Seattle trace (aspect ratio optimized for printing).

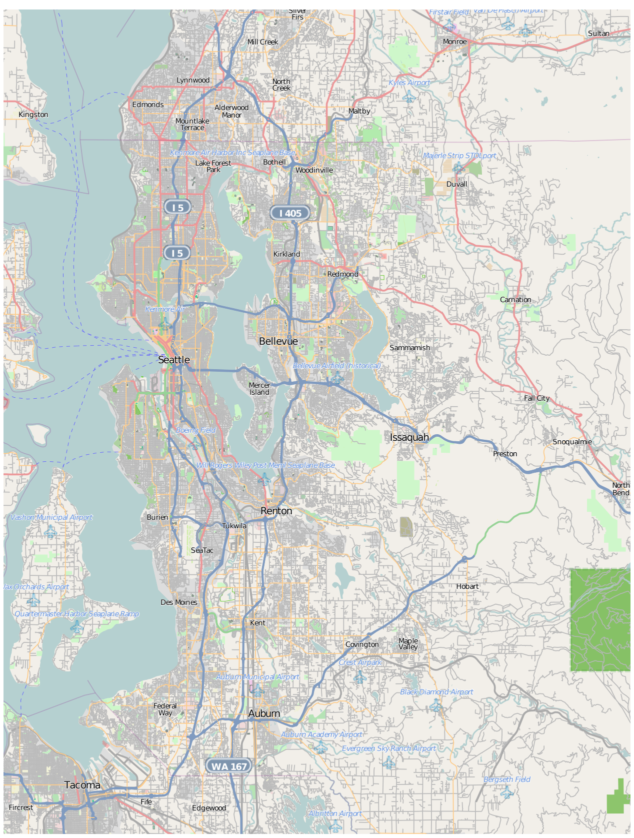

Figure 3. Map of the Seattle area (provided by OpenStreetMaps) as a visual reference. Note that Mercers Island in the middle of the map is also clearly visible in the plot of position updates in the previous figure.

offsets between the coordinates of the Seattle traces and the commonly used WGS-84 system is unknown. For this reason both maps are kept in their original format, since a conversion would be based on assumptions and manual georeferencing, and therefore unavoidably introduce inaccuracies.

The transformation and offsets between the coordinates of the Seattle traces and the commonly used WGS-84 system is not documented besides the statement that “coordinates are in feet and were computed from the latitude and longitude values reported in the raw traces”[14]. Unfortunately these raw traces are not available. Manual georeferencing implies the raw traces are state plane system coordinates (Washington State Plane North) with a proprietary offset subtracted. Nevertheless, we decided to keep both maps in their original format, since a conversion would be based on assumptions and manual georeferencing, and therefore unavoidably introduce inaccuracies.

B. *Chicago Trace*

The Chicago mobility trace [15] was obtained from the Chicago Transport Authority (CTA) Bus Tracker API, which is available and documented at [20]. Automated vehicle location systems (AVL) on the buses send position updates to a central server at CTA. These positions are based on GPS reception with a backup odometry system that is used if GPS reception is unavailable and also for plausibility checks (GPS receivers occasionally report bogus positions if the reception is bad, e.g. in areas with many high buildings). For a continuous duration of 18 days in November 2009, a script was used to store timestamped vehicle identifiers and WGS-84 [21] coordinates from the Bus Tracker API in a database. Moreover the trace contains the route and trip identifiers, direction and destination of the trip, and a pattern identifier as a georeferenced representations of the trip.

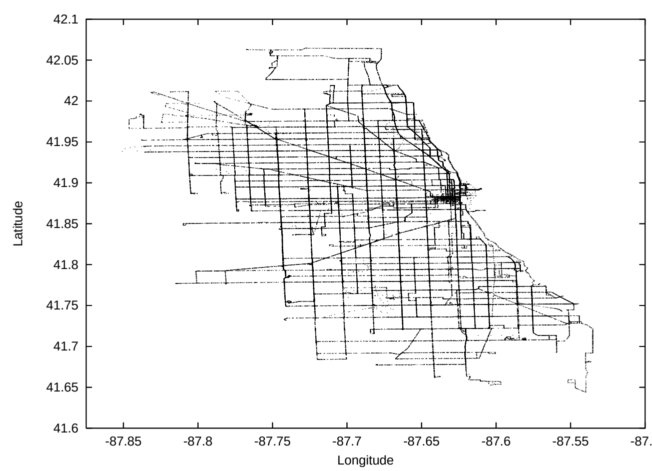

Figure 4. Position updates of the Chicago trace (aspect ratio optimized for printing).

An advantage of the Chicago trace is the extensive meta-data that is available. It includes the names and geolocations of stops as well as definitions of routes and timetables, which are publicly available via Google Transit (http:

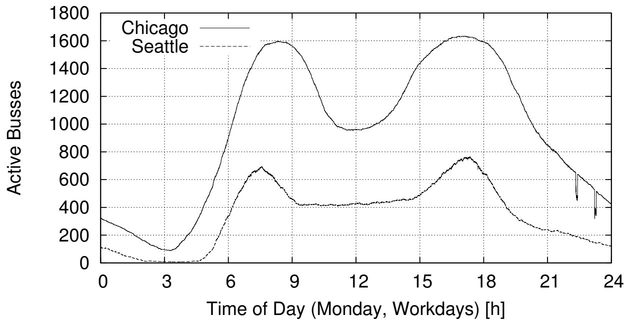

Figure 5. Number of active buses on Mondays.

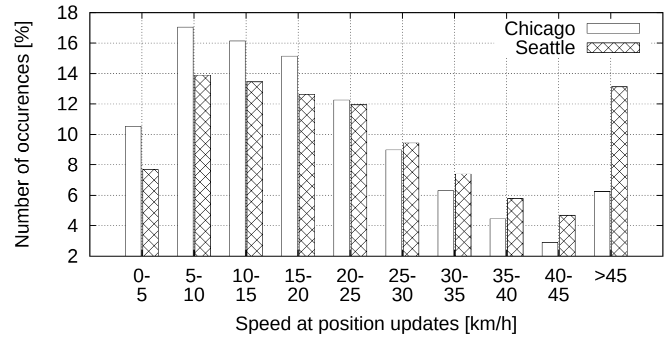

Figure 6. Distribution of vehicle speeds.

//www.google.com/intl/en/landing/transit/text.html) in a documented format (http://code.google.com/transit/spec/transit_feed_specification.html). This meta-data is essential for the development and evaluation of ad-hoc routing algorithms in a public transport network.

Figure 4 shows 10000 consecutive position updates from the Chicago trace. Again, routes are clearly visible because of the large amount of samples. For this diagram the original unit of WGS-84 degrees of latitude/longitude were maintained. This standardized coordinate system is widely used, e.g. in geoinformation systems and map databases. For this reason the position updates and metadata (e.g. locations of busstops) can be processed without additional transformation, which may introduce inaccuracies. Therefore, it is possible to display data to be analyzed as an overlay to cartographic material, e.g. as in figure 13.

III. Seattle and Chicago Traces: Similarities and Differences

A. Amount and Interval of Position Updates

The interval of position updates is important for the resolution of a trace. The more updates (samples) are sent by the AVL systems in a given period of time the better the resolution. Unfortunately, the update rate is bounded, since sending updates requires usage of limited resources (e.g. usage of the shared voice/data radio system to send position data). For simulations, it is necessary to create continuous node movement by extrapolating [22] the discrete position updates. Therefore, it is desirable to have short update intervals.

Comparing the 2001 traces of Seattle [16] with our 2009 traces of Chicago [15] shows several similarities but also major differences. In order to achieve a fair comparison a Monday workday in November is selected from both traces. During this period the vehicles in Seattle sent 327880 valid position updates and those in Chicago sent 1736431, more than five times as many. The amount of active vehicles peaks to 1647 in Chicago and 765 in Seattle, as can be observed in Figure 5. Both traces show similar distinct rush hour spikes and vehicles move mainly at low speeds under 35km/h.

However, the speed distribution plotted in Figure 6 shows that vehicles drive more often at higher speeds in Seattle, which is due to a more rural area of operation in contrast to the denser downtown traffic in Chicago.

Further, the update interval shown in Figure 7 is shorter in Chicago, leading to a larger amount of position updates and to shorter distances between consecutive positions as shown in Figure 8. The rate is mainly between 20 and 40 seconds in Chicago, but in the order of 1-2 minutes for the Seattle trace, as shown in figure 7. Therefore, the Chicago trace is better suited as a basis for generating realistic mobility traces for simulations. It contains more detailed, well-grounded base data compared to the Seattle trace. Due to the lack of supporting points in the latter, more extrapolations are needed which lower the quality of simulations and other studies based on the Seattle data.

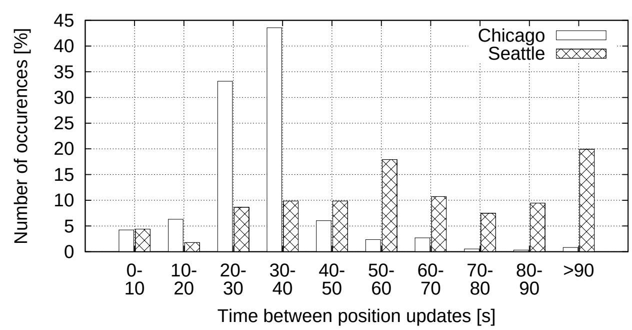

Figure 7. Distribution of time between consecutive position updates.

B. Vehicle-to-Line Assignment

The existence of lines (i.e. predefined routes) is an important property of public transport networks. Moreover, lines describe future vehicle trajectories and therefore offer interesting opportunities for ad-hoc and delay tolerant routing algorithms. For this reason it is important to understand the dynamic relationship between specific vehicles and assigned lines. Usually there is no fixed assignment of vehicles to routes, because each vehicle is dispatched to a random route at the

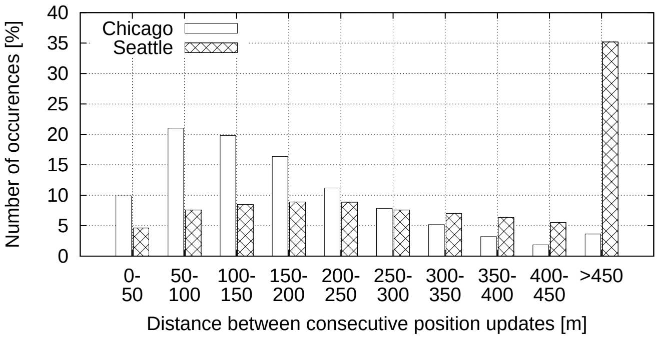

Figure 8. Distances between position updates.

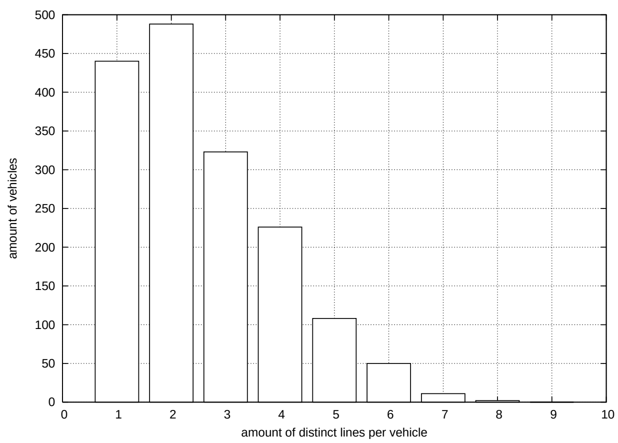

Figure 9. Chicago vehicle to line assignment for a five hour time window (Monday morning 7h-12h)

beginning of a shift. [23] Moreover, during one shift vehicles frequently change routes in order to increase usage rate by reducing deadheads and waiting times.

An analysis of the Chicago vehicle-to-line assignment shows a non-deterministic behavior similar to that described in [23]. Moreover, it is also observable that a significant amount of vehicles changes from one line to another during a shift. In figure 9 each bar shows the amount of vehicles (y-axis) and the number of distinct lines (x-axis) they operate on, during the Monday morning five hour time window described above. This means that only 440 of 1688 vehicles operate on the same line during these five hours, while the remaining vehicles change lines one or more times. Figure 10 shows the amount of vehicles/lines for the whole trace (18 days). It is observable that the majority of vehicles operates on 15 or more lines.

The Seattle trace shows a similar behavior, although with a different clearness. In a five hour window (workday Monday morning 5-12h, equivalent to Chicago) shown in figure 11 there are much fewer vehicles changing lines. Moreover, changes are less frequent, but nevertheless not uncommon. Figure 12 shows the vehicle to line assignment over 16 consecutive days. Interestingly, in Seattle there are slightly more than 40 vehicles

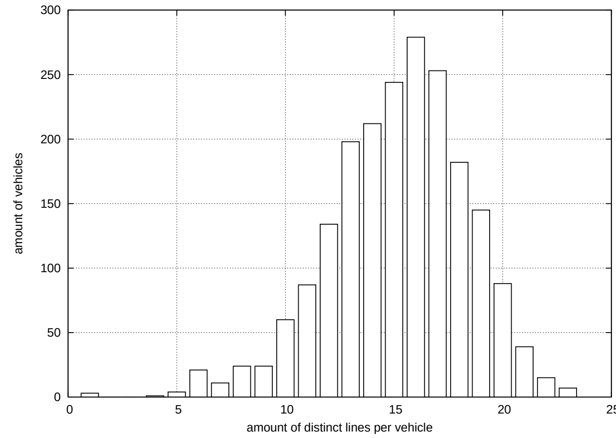

Figure 10. Chicago vehicle to line assignment for the whole duration of the trace (18 days)

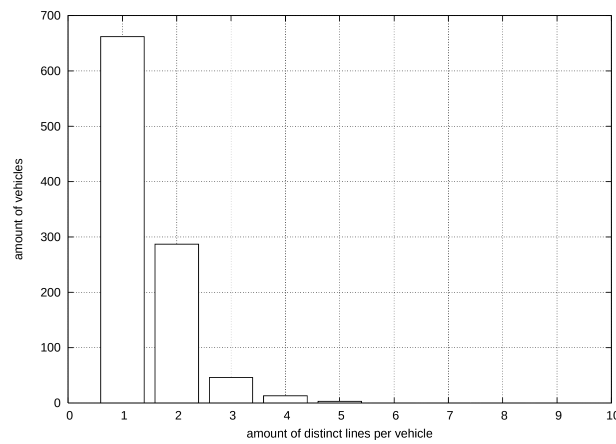

Figure 11. Seattle vehicle to line assignment for a five hour time window (Monday morning 7h-12h)

that exclusively operate on a single line, which is significantly more than in Chicago. However, this exclusive operation is still very uncommon considering the large amount of vehicles that change lines.

C. Vehicle Density

The density of vehicles significantly impacts the performance of VANETs and DTNs. Moreover, knowledge on density distribution of vehicles with specific properties is valuable for the design of routing and scheduling algorithms. The GPS position updates of the Chicago trace provide density information. Figure 13 shows a snapshot of vehicle positions plotted on a map of the Chicago area. There is a clear accumulation of vehicles at the city center.

For a more detailed analysis a grid of 0.001 was laid over the WGS-84 coordinates of the position updates. Then the

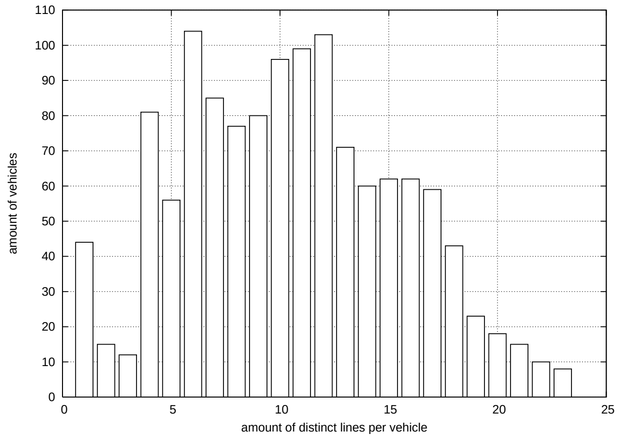

Figure 12. Seattle vehicle to line assignment for the whole duration of the trace (16 days)

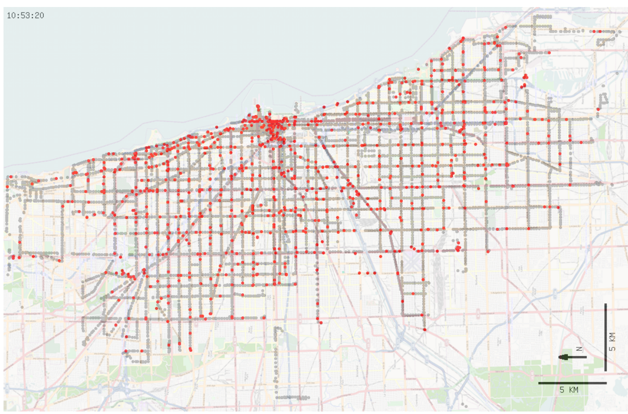

Figure 13. Snapshot of vehicle density. Red dots indicate vehicles, gray dots indicate stops. The background map is based on OpenStreetMaps.

amount of position updates for each resulting tile was extracted from the trace database for specific time windows. The amount of updates within each tile divided by the amount of all updates corresponds to the probability to encounter a vehicle in that tile, because of the regular time intervals between position updates. Figure 14 shows the amount of updates per tile for a five hour time window. Interestingly, the distribution looks different from what one would intuitively expect on the basis of the snapshot in figure 13.

Besides the city center, there are other areas with high amounts of updates. This happens because slow and non-moving vehicles stay longer in a tile and therefore send more updates. Especially the bus garages and the bus-stops where off-duty vehicles/drivers take their break show this accumulation. This means that there is a higher probability to encounter a vehicle in such places. However, these vehicles are not moving for certain periods, so it cannot be assumed that these areas are generally “better” for the performance of VANETs/DTNs.

In the next step of the analysis, vehicles operating on the same line are isolated. Figure 15 shows the density of updates for line 8. Not surprisingly the ’footprint’ of line 8 is clearly visible, but again there are tiles with a significantly higher encounter probability. As another example line 21 is

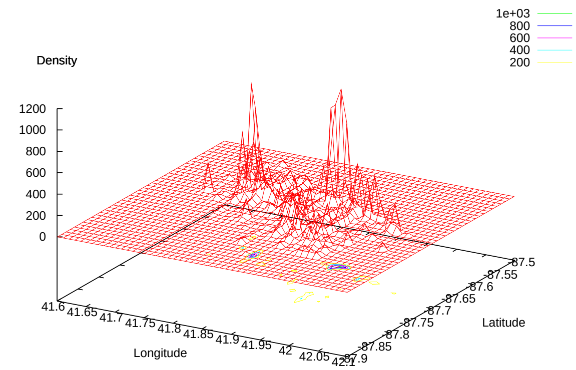

Figure 14. Chicago trace: Density of position updates (corresponds to vehicle density) for a five hour time window (Monday morning 7h-12h)

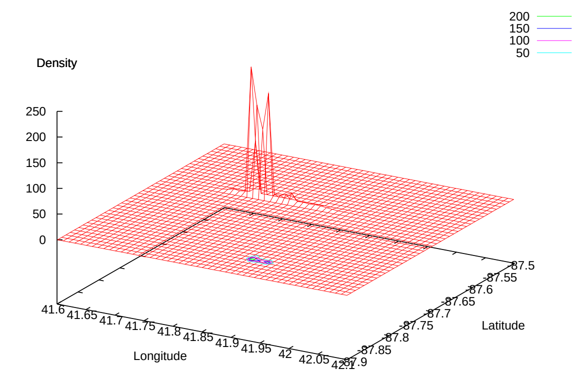

Figure 15. Chicago trace: Density of position updates on line 8 for a five hour time window (Monday morning 7h-12h)

plotted in figure 16. It has a similar distribution, but another orientation. In conclusion the encounter probability is not evenly distributed on a single line.

The density data plotted in the diagrams has for example the potential to be exploited for a routing approach, because grid datastructures are relatively easy to compute. For example, the density of different lines can be used to identify tiles in which there is a large probability that vehicles of different lines encounter each other.

Figures 17 and 18 show the spatial distribution of 10.000 consecutive position updates in the Seattle trace. The distribution of updates directly corresponds to the distribution of vehicles, since updates are transmitted at regular intervals. It is highly uneven as the normalized amount of updates in tiles of 100m$\times$100m in figure 17 depicts. The big agglomeration is located at the downtown area and can be explained by the denser public transport network in this area. The suburban and rural areas are much sparser. For this reason the downtown area appears as a big spike in the plot. In figure 18 the downtown area is zoomed in by choosing a smaller range of easting/northing (note the coordinates in the diagrams to observe the zoomed-in area). The close-up shows that the single spike is in fact more differentiated. Now it is possible to

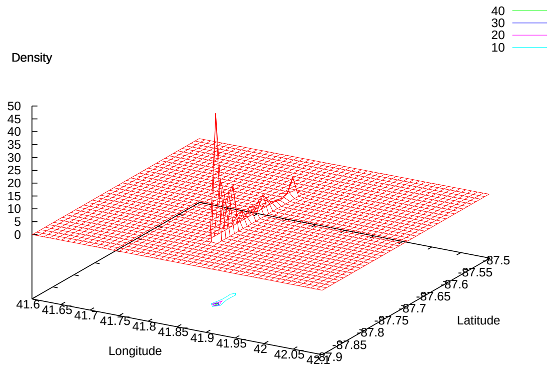

Figure 16. Chicago Trace: Density of position updates on line 21 for a five hour time window (Monday morning 7h-12h)

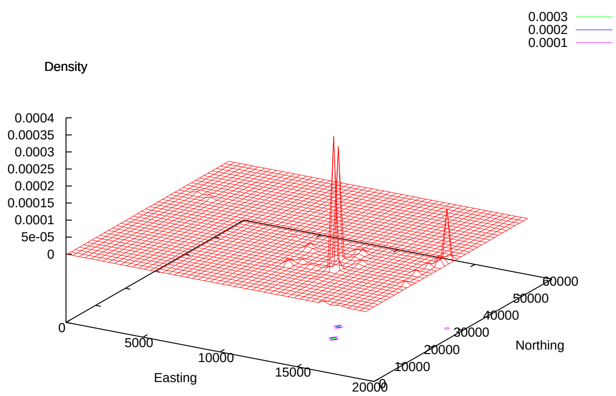

Figure 17. Seattle trace: Normalized spatial density of position updates.

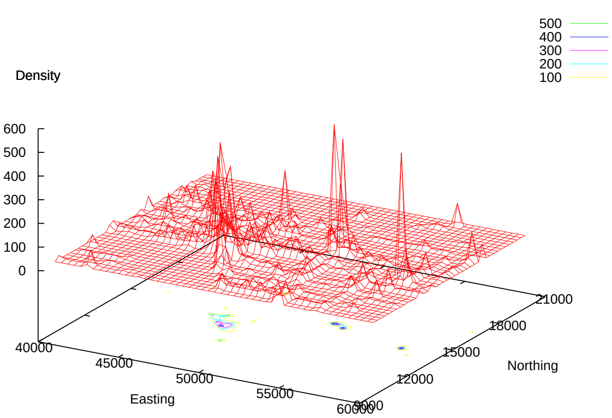

Figure 18. Seattle trace: Spatial density of position updates within the city area.

recognize longish patterns, which are in fact frequently used roads.

IV. Conclusions

Table 1 summarizes the similarities as well as the differences of both large scale movement traces. Both traces were recorded over a duration of more than two weeks, which is sufficient to analyze weekly dynamics such as working day and weekend cycles. The maximum amount of active vehicles (i.e. on-duty vehicles with active AVL systems) in the Chicago trace is more than twice as high as in Seattle. It is important to note that the covered areas of both public transport systems are very different, not only in size but also in density and road traffic properties (e.g. inner city vs. urban). This difference is also clearly visible in the three-dimensional spatial distribution plots and by the slightly higher vehicle speeds in the Seattle area. Moreover, it also becomes obvious by the difference in vehicle-to-line assignment that the public transport systems are operated in slightly diverse way. Unfortunately, the traces were recorded with different coordinate systems, which is induced by the position data generated by different kinds of proprietary AVL systems. Therefore, there is also a dissimilar extent of data fields in the traces. While the Seattle trace contains only basic data, there is a rich set of additional meta-data available for the Chicago trace. Moreover, the position update interval of the AVL systems used in Chicago is significantly shorter. For this reason (and also because of the larger amount of active vehicles in Chicago) there are more than five times as many updates in the Chicago trace. However, although there are many differences, there are also similarities in the dynamics of mobility. Very distinct rush-hour spikes as well as weekday/weekend patterns are present in both traces, and the amount of active vehicles over time follows a very similar pattern.

We believe that such traces and the understanding of their characteristics are important to design, analyze, and evaluate future opportunistic vehicular networks. Such communication systems can be a useful part of future smart cities. The size of the discussed traces allows for detailed, close to real-world studies. Yet, due to the large size of these traces, but also of future systems which may use such bus-based communication facilities, high-performance computing and simulation approaches are needed.

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Table I. OVERVIEW ABOUT SIMILARITIES AND DIFFERENCES BETWEEN THE TWO TRACES.

	Seattle 'Trace5' [14]	Chicago [15]
duration	16 days	18 days
max. amount of active vehicles	765	1647
covered area (enclosing rectangle)	$\sim$30×25 km	$\sim$55×85 km
coordinate system	Washington State Plane North	WGS 84
AVL system type	signpost + odometry	GPS + odometry backup
trace data	timestamp, position, route	timestamp, position, route, trip, direction, destination
available metadata	-	timetables, stops, route and trip definitions
position update interval	26-120s	20-40s
amount of updates (5h)	327 880	1 736 431
lines per vehicle, min/avg/max (5h)	1 / 1.4 / 5	1 / 2.6 / 8

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