Vehicle Position Determination — Using Markers and Speed Reports

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***Abstract*—The use of cell phones as data-collection devices for obtaining automotive traffic-flow information provides the potential for instrumenting large numbers of vehicles at a minimal cost. Effectively incorporating cell phones as sensors in traffic-flow collection systems requires a clear understanding of the accuracy of the data produced by each cell phone. Previous experiments and field trials have typically measured the accuracy of cell-phone data at large — comparing all of the collected cell-phone reports across a given segment of the road against data obtained with traditional techniques such as loop detectors. The approach that we take in this research differs by comparing each individual cell-phone report with the known position of the vehicle at the time of the report. This paper describes the technique we used for accurately determining the actual speed and position of a vehicle at any given point in time during a test trip by using published map data, speed reports from the vehicle itself, position reports from a hand-held GPS unit with an external antenna, and operator inputs.**

***Index Terms*—GPS, traffic flow, cell phones, data collection.**

I. INTRODUCTION

Rapid advances in cell-phone technology coupled with the penetration of cell phones into the general population provide an opportunity to utilize cell phones as mobile probes that provide real-time traffic-flow information. Multiple studies and experiments show the feasibility of using cell phones to collect both basic traffic-flow information such as vehicle position and speed [1][2] and additional types of information including road conditions, bumps, braking conditions, and the presence of honking [3].

Incorporating cell phones into traffic-flow data-collection techniques involves some challenges that we must address, most notably, determining the accuracy of the reports that cell phones generate [4][5][1]. We can determine the accuracy of data reports by comparing the reports with the known ground truth. In most cases, the ground truth for individual vehicles is not easy to determine. Most field tests utilize passive collection techniques, such as inductive loops, to provide the ground truth for comparison purposes.

Rather than compare collected data in the traditional sense, this research focuses on individual cell-phone reports and comparing each report with the ground truth for that cell phone at the time of the report generation. In order to carry out this comparison, we must determine the ground truth for a given vehicle at any point in time. With our approach there is no need for physical roadway support such as loop detectors, and our approach works over the entire length of any desired roadway, not just where sensors are available. This paper describes the technique of combining various inputs in order to determine the vehicle's precise location and speed at any point in time.

The next section of this paper discusses related work, and Section III highlights some of the challenges that we face while also providing an overview of our approach. In subsequent sections we explain how we use map data, vehicle speed data, GPS data, and operator inputs. Next we detail the calculations that we use for determining the actual position of a test vehicle at any given time, and then we itemize the steps for finding the vehicle position. Finally, we summarize the results of our work and mention what our next steps will be going forward.

II. RELATED WORK

The growing interest in using cell phones in probe vehicles to detect and report traffic-flow conditions has generated a number of research projects and experiments. Some of these experiments exploit the characteristics of the cellular network to calculate a vehicle's location and speed [6][7] while other experiments utilize the GPS capabilities available in most cell phones today [8][1].

While assessing the accuracy of the cell phone data, most of these experiments compare the data collected by cell phones with that collected by traditional means — most often inductive loops embedded in roadways. Loop sensors or other types of point sensors count the number of vehicles that pass by the sensor and provide data for calculating the average speeds and time of traversal for the segments of the road between adjacent sensors [9]. In order to compare the accuracy of cell phones against this traditional data, some of these experiments average cell-phone reports over the same segments of the road and compare them against the data that the inductive loops provide. Other tests include additional data such as the speed of the vehicle obtained directly from the vehicle [10]. The resulting comparisons provide insight into the overall accuracy of the cell-phone reports but do not characterize the accuracy of individual cell phones. Furthermore, this technique provides no insight

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into the particular factors that directly affect a cell phone's accuracy.

Our overall research focuses on optimizing data-collection strategies by incorporating knowledge about the accuracy of individual cell phones. Minh and Kamioka suggest a similar technique in their research with their Pinpoint approach [11]. Their concept of sending the "right" data at the "right" time aligns closely with our research approach. A key distinction of our research involves incorporating the reported accuracy of individual cell phones into the reporting algorithms.

In order to characterize the accuracy of individual cell phones under various conditions, we take a different approach from the works cited above. Our field tests constrain the probe vehicles to a known path and the phones to various positions in the vehicle. In addition, we incorporate outside information including map data, speed information from the vehicle itself, and operator input. This paper describes our techniques for determining the ground truth, exactly where the probe vehicle is at any given point in time during the experiment, for each cell-phone report — something typically reserved for simulations. Establishing the ground-truth data for each individual report allows us to analyze the accuracy of each individual cell phone under a variety of conditions.

III. CHALLENGE AND APPROACH

Measuring the accuracy of a position report from a static (i.e., not moving) cell phone is easy. Simply put the cell phone at a known location, and compare the position report from the cell phone to the actual location of the cell phone. However, to use cell phones for collecting vehicular traffic-flow data, we must get reports from cell phones that are inside moving vehicles. Multiple factors may affect the accuracy of a cell phone's speed-and-position reports when the cell phone is in a moving vehicle. For example, the cell phone may not have a consistently clear view of the sky because of terrain, buildings, or the structure of the vehicle itself. Also, the cell phone may not be able to produce accurate reports due to the simple fact that the cell phone is moving, especially when the vehicle is changing direction.

Before we can assess the accuracy of speed-and-position reports from a cell phone in a moving vehicle, we must somehow determine the *actual* speed and position of the vehicle. Our goal in this paper is to determine the actual speed and location of a test vehicle at any given time in a test trip so we can measure the accuracy of a cell-phone report whenever the cell phone makes a report. We can determine the actual speed directly from the vehicle itself by using the vehicle's diagnostic interface. However, determining our exact position on the road is a bit more of a challenge. By combining static data published by the Arizona Department of Transportation (ADOT) with dynamic data that we collect during the test run, we can determine the vehicle's actual location at any point in time.

Our technique utilizes map data published by the Arizona Department of Transportation (ADOT), speed data that we collect from the vehicle, GPS data that we collect from a hand-held GPS unit with an external antenna, and operator input that we collect via a laptop PC in the vehicle under test. Our data-collection procedures [12], [13], [14] dictate that we follow the same center-line path that the ADOT data-collection vehicles used, so we have a known path. In addition, the test vehicle will be passing precisely located milepost markers, and the operator will use the laptop PC to flag the milepost markers in the data log, thus giving us a set of time-correlated positions. We can determine the appropriate milepost marker corresponding to each item in the operator log by using the GPS reports at or near the time of the operator's mark.

IV. MAP INFORMATION

ADOT provides two relevant sets of map information — data for the centerline track and data for the milepost markers. The data values for the centerline track provide points in the middle of our lane along the path that we will follow, mirroring the ADOT collection vehicles as part of our collection strategy. The data values for the milepost markers identify the locations (on the centerline track) of the mile markers along the path. By marking the time when we pass each milepost, we will be creating a set of known positions at specific points in time.

Note that the data values for a milepost marker conveniently specify the geographical coordinates of the centerline point corresponding to the mile marker, not the physical location of the milepost marker itself. We are interested in the position of our vehicle as it passes the milepost marker, so the data values for the milepost markers in the ADOT data are exactly what we need. Figure 1 shows how the centerline points and the milepost points relate to each other.

The centerline points are not regularly spaced, but vary according to the curvature of the road. Straight segments of the road require relatively few data points while curved segments of the road require multiple points. Milepost markers, on the other hand, define regular intervals of one mile and are evenly spaced one mile from each other.

V. VEHICLE SPEED DATA AND GPS DATA

We can retrieve the vehicle's speed directly from the vehicle. By tapping into the vehicle's diagnostic port and requesting speed data, we can collect the actual speed of the vehicle throughout the test trip. All vehicles supporting the onboard diagnostics (ODB-II) interface provide a basic set of powertrain parameters — speed being one of those parameters. The ODB-II protocol allows us to query the data once per second, which will be frequent enough for our use since our test vehicle will not change speed dramatically from one second to the next.

In order to request the speed information from the vehicle, we are using a vehicle interface adapter from Multiplex Engineering. This adapter converts the laptop interface (RS-232 and command packets) to SAE-J1708 diagnostic requests (ISO-9141 signals and SAE-J1708 packet data). The data-collection program in the laptop PC contains a thread to do the following:

- Establish communications with the test vehicle.
- Periodically (once per second) send a request for the speed of the vehicle.
- Read the response from the vehicle.
- Convert the response to vehicle-report format [14].
- Send the report to the logging system.

The logging software timestamps each vehicle speed report. These reports give us a set of speed reports of the form (v, t) where v represents the vehicle's speed at the time t.

Figure 1 illustrates the vehicle data collections in relation to the map information. Notice that we collect the vehicle data at regular intervals with a period of approximately one second.

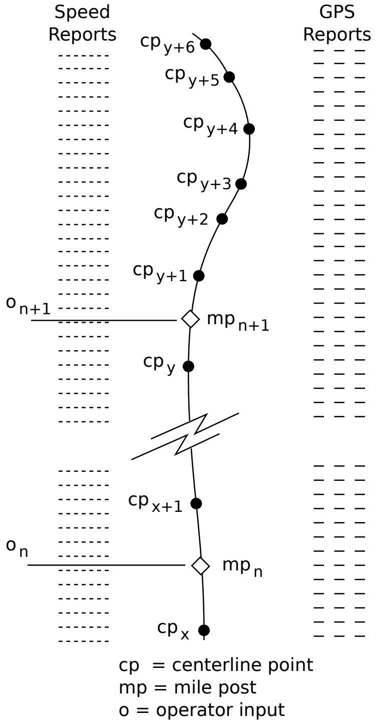

Fig. 1. Map Info with Collected Data

We collect GPS data from a hand-held GPS unit with an external roof-mounted antenna in a similar fashion. The GPS unit reports its data with a period of one second. The data-collection system receives these reports and logs them. Even though the GPS unit reports data with the same frequency as the vehicle speed data, the reports are not synchronized in any manner. As the next section explains, the GPS reports provide the location of the vehicle with more than enough accuracy to determine exactly which milepost marker the vehicle has just passed when the operator makes an entry to mark the passing of a milepost. We thereby fix our vehicle position at a specific location and at a specific point in time. Figure 1 shows how the GPS reports relate to the map information and the speed reports.

VI. OPERATOR INPUT

Operator inputs provide the key component to determining the exact vehicle position at any point during the test run. By creating a marker in the logs whenever the vehicle passes a milepost, the operator establishes a set of known positions, at each milepost marker, at specific times during the test run [14]. The software records the operator input in the logs as a simple landmark notation that includes the timestamp but does not include any positional data.

We collect GPS reports from a hand-held GPS unit at one-second intervals throughout the test trip. We use the GPS reports only to determine the closest milepost at each operator's mark. Once we have determined which milepost the operator was marking, we have established a known position at a specific moment in time. Since the mileposts are one mile apart, we need only enough accuracy from the GPS reports to pick between two positions that are one mile apart. This modest accuracy requirement is well within the range of the hand-held GPS with an external antenna. Figure 1 illustrates the operator inputs at each milepost marker.

VII. DISTANCE CALCULATIONS

After we have collected the data, we have all of the the information necessary to determine the vehicle position at any point in time. We have a fixed path, several known milepost positions at specific points in time, and known vehicle speed at numerous points between our known milepost positions. The approach that we take is similar to the one that people use in computer animation for moving an object along a curved path [15]. We calculate the arc length for each segment, sum those distances to obtain the total distance traveled between known positions, determine the scaling factors required to project the segments onto the known path, and, finally, use the adjusted formulas to determine the absolute position of the vehicle for any given time t.

A. Calculating Segment Distances

Figure 2 illustrates the speed-time relation, where each point represents one speed report — a specific speed at a given point in time. The shaded areas below the speed line represent the distance covered between two speed reports.

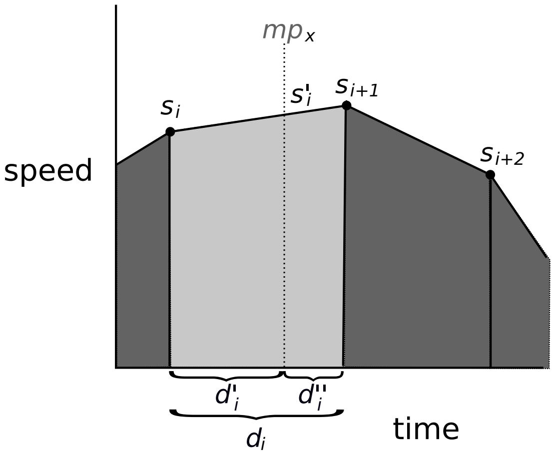

Fig. 2. Speed-Time Relation

Each speed report s_i has two components and occurs in the data as the pair (v, t) where v represents the vehicle's velocity at time t. Individually, we will refer to these components as v_i and t_i. The distance covered between speed reports s_i and s_{i+1} corresponds to the shaded area below those two reports — d_i. When we need to determine a speed at a time between t_i and t_{i+1} we will generate an interpolated speed report s'_i. We denote the distance between s_i and s'_i as d'_i, and we denote the distance between s'_i and s_{i+1} as d''_i.

We can calculate the distance covered between s_i and s_{i+1} as:

$$d_i = \int_{t_i}^{t_{i+1}} f(t)dt \tag{1}$$

where $f(t)$ represents the velocity of the vehicle over time.

However, the only data values that we have are the known speeds at t_i and t_{i+1}. Given that the speed reports occur at a rate of approximately one per second and based on the physics of vehicles in motion, we can safely assume a constant acceleration/deceleration between t_i and t_{i+1}. We can therefore simplify Equation (1) to the following:

$$d_i = v_{avg}(t_{i+1} - t_i) \tag{2}$$

which, when given that

$$v_{avg} = \frac{1}{2}(v_i + v_{i+1}) \tag{3}$$

yields:

$$d_i = \frac{1}{2}(v_i + v_{i+1})(t_{i+1} - t_i) \tag{4}$$

If the milepost reports were synchronized with the speed reports, then we could calculate the total distance between two mileposts by summing the distances covered by each speed report. For example, if s_i occurred at mp_x and s_{i+n} occurred at mp_{x+1}, then we could calculate the total distance, D_x, between the two mileposts as:

$$D_x = \sum_{j=i}^{i+n-1} d_j \tag{5}$$

Since the milepost reports typically fall between two speed reports rather than being synchronized with a speed report, we can generate an interpolated speed report to coincide with the time of the milepost report (t'). If s_i is the latest speed report before the milepost report, then we can calculate the velocity for the generated speed report s'_i at t' as follows:

$$tan(\Theta) = \frac{v_{i+1} - v_i}{t_{i+1} - t_i} \tag{6}$$

$$v' = v_i + (tan(\Theta)) * (t' - t_i) \tag{7}$$

$$v' = v_i + \left(\frac{v_{i+1} - v_i}{t_{i+1} - t_i}\right)(t' - t_i) \tag{8}$$

The generated speed report s'_i would be (t', v'). We can generate a similar speed report s'_{i+n} for the ending milepost by using the speed report s_{i+n} that was the latest speed report before the mp_{x+1} report for the next milepost marker. For each speed report that falls just before a milepost report, we can separate the distance into two areas, d'_i and d''_i as shown in Figure 2. Note that the milepost report can be anywhere between the two speed reports. With these definitions, we can rewrite Equation (5) for calculating the distance between the two mileposts mp_x and mp_{x+1} as:

$$D_x = d''_i + \sum_{j=i+1}^{i+n-1} d_j + d'_{i+n} \tag{9}$$

B. Aligning Calculations with Map Data

We can calculate the total distance between operator inputs (two known positions at marked times) by using Equation (9) of Section VII-A. This calculated value will most likely be different from the actual value (from the ADOT-provided data). A variety of factors can account for this difference: inexactness of the operator's marks, speedometer error, inaccuracy of the ADOT-provided data, etc.

Based on Equation (9), each d_i accounts for a given portion of the entire length of D_x. Specifically, each d_i represents d_i/D_x of the total distance D_x. If k is the scale factor such that:

$$kD_x = L_x \tag{10}$$

where L_x is the ADOT-provided distance over the same two milepost markers, then

$$k = \frac{L_x}{D_x} \tag{11}$$

and we can rewrite Equation (9) to reflect the distances scaled to yield L_x as the result:

$$L_x = kd''_i + \sum_{j=i+1}^{i+n-1} kd_j + kd'_{i+n} \tag{12}$$

VIII. DETERMINING VEHICLE POSITION

We can now determine the position of the test vehicle at any given time t (corresponding to a report from a cell phone whose accuracy we are trying to measure) by performing the following steps:

- Determine the milepost reports that surround time t (M_x, M_{x+1}).
- Retrieve all speed reports between and encompassing M_x and M_{x+1}.
- Calculate D_x from Equation (9).
- Calculate L_x from ADOT-provided data, and determine k from Equation (11).
- Sum the adjusted distances between M_x and the speed report just before time t.
- Add the partial distance covered in the segment containing t by generating an artificial speed report as in Equation (8).
- Travel the known path from M_x toward M_{x+1} for the calculated covered distance.

IX. CONCLUSION

We now have a method for determining the actual position of a test vehicle at any given point in time, so we can process the cell-phone GPS reports and calculate the error value for each report. In a batch-processing mode following the conclusion of a test run, we can optimize the steps listed above by storing the calculated distances for each individual segment as well as the scaling values and distances between milepost reports.

The procedures we have described in this paper provide the foundation for evaluating the accuracy of the reports from a cell phone in a moving vehicle. Our inputs include ADOT data to specify a known path of travel, operator inputs to place the vehicle at known positions at specific times, and the speed data that the vehicle itself reports.

X. FUTURE WORK

With the ability to determine the accurate position of a test vehicle along a traveled path at any given point in time, we plan to take cell-phone GPS reports across a number of test runs and begin creating accuracy models for different types of phones under various conditions. These models will help determine optimal methods for collecting data and processing that data both for real-time traffic-flow information and for data-mining applications.

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