DECISION-RULE ALGORITHM FOR MAP-MATCHING APPLIED TO INTELLIGENT WINTER MAINTENANCE DATA

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ABSTRACT

Intelligent winter maintenance vehicles are equipped with automatic vehicle location technology, including Differential Global Positioning System (DGPS) receivers and various additional sensors that collect equipment status and material usage data. DGPS points are associated with the nearest roadway by calculating minimum perpendicular distances between each centerline representation and the DGPS points. Highly accurate roadway maps and DGPS measurements are not always available. Thus, spatial mismatches may occur at converging and diverging roadways, and intersections. Decision-makers use winter maintenance performance measures, which are sensitive to spatial mismatches and need to be resolved before calculating them. This paper presents a decision-rule map-matching algorithm that resolves spatial ambiguities by determining the correct roadway on which the vehicle is traveling. The algorithm computes shortest paths between snapped DGPS points using network topology and turn restrictions. A path is considered viable, and locations for the snapped DGPS points correct, if similarity exists between values of calculated and recorded vehicle speeds. If a path is not feasible, DGPS points are snapped to alternative roadway contained within their buffers, shortest paths are recalculated, and speeds are again compared.
Keywords: Global Positioning System; Winter maintenance; Map matching algorithm

RESUMEN

Los vehículos inteligentes, que mantienen las vías durante el invierno, están equipados con tecnología de localización automática de vehículos en conjunto con receptores de sistemas de posicionamiento global diferencial (DGPS) y varios sensores adicionales que capturan información sobre el estatus del equipo y el uso de materiales. Los puntos DGPS son asociados a la vías más cercanas calculando la mínima distancia perpendicular entre los ejes de la calzada y dichos puntos. No siempre se pueden obtener buenas mediciones DGPS ni mapas digitales que representan la red vial de manera exacta. Por lo tanto, discrepancias espaciales pueden ocurrir en intersecciones o en calles que convergen o divergen. Los gerentes toman decisiones empleando medidas de desempeño que son sensibles a estas incompatibilidades y que deben ser resueltas antes de utilizarlas. Este trabajo presenta un algoritmo "map-matching" basado en reglas de decisión que soluciona las discrepancias espaciales al determinar el eje de calzada correcto por el cual el vehículo transita. El algoritmo propuesto calcula las rutas más cortas entre los puntos DGPS, que están asociados a una vía, utilizando la red topológica y las restricciones en virajes. Si existe similitud entre la velocidad calculada y la velocidad registrada, entonces la ruta obtenida es considerada viable y las ubicaciones asociadas a los puntos DGPS están asociados correctamente. Si la ruta no es factible, los puntos DGPS son asociados a ejes de calzada alternativos que están contenidos dentro de sus buffers, luego las rutas más cortas y las velocidades son calculadas nuevamente.
Palabras claves: Sistemas de Posicionamiento Global, Mantención invernal, Algoritmo "map-matching"

1. INTRODUCTION

Many transportation agencies in the United States have experimented with and deployed advanced technologies for winter operations in order to keep the highway system at a high level of service, clear of snow and ice, and safe for driving. As they travel, intelligent winter maintenance vehicles collect speed, environmental (e.g., pavement and air temperature), equipment status (e.g., plow up or plow down), and material usage data (e.g., salt application rate) along with Differential Global Positioning Systems (DGPS) coordinate measurements. In Wisconsin and Iowa, vehicle data are collected in the form of message sets from all sensing devices, including DGPS receivers, blade position sensors, material spreading sensors, and air and pavement temperature sensors as shown in Figure 1 (Vonderohe et al., 2002). These data are transmitted to a central dispatch location in real-time, as often as every two seconds, and are also stored on-board the vehicle for later retrieval, processing, and analysis. The latter consist of the computation of performance measures that provide a basis for decision-making on allocation of resources (i.e. labor, materials, and equipment) and enhancement of overall winter operations performance. Examples of performance measures are labor cost per storm and total quantities of salt and sand per storm event. Accurate calculation of performance measures for winter operations is imperative since decision makers use them as indicators of how well their service and procedures meet guidelines and satisfy expectations. Decision makers utilize performance measures to evaluate achievement of goals such as minimizing environmental impacts, managing annual winter maintenance budgets, and providing good winter driving conditions.

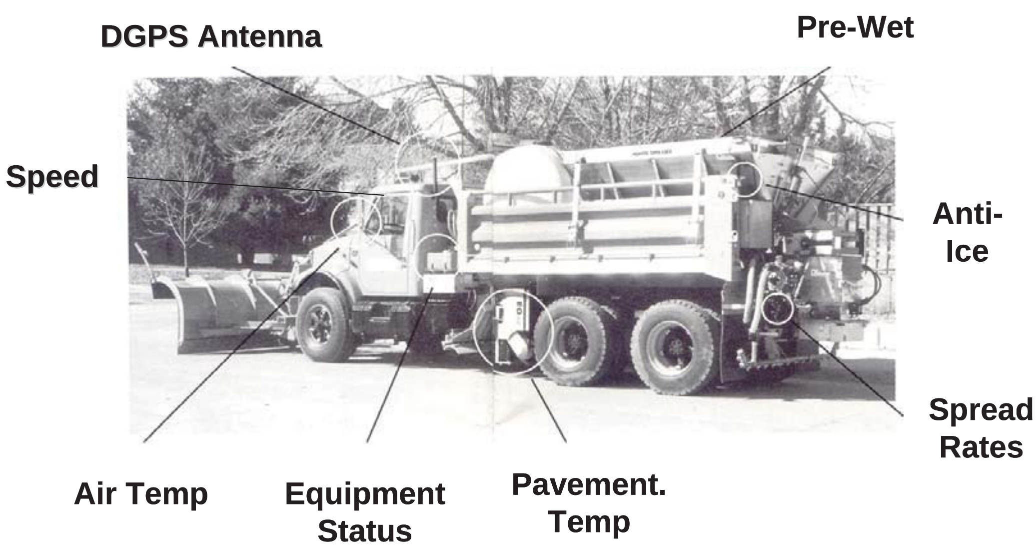

Figure 1: Typical Winter Maintenance Vehicle Wired With Sensors and DGPS Receivers

2. PROBLEM STATEMENT

Transportation agencies use spatial data to locate events and infrastructure such as traffic accidents and bridges on transportation systems. Various methods (e.g. distance measurement instruments, linear referencing methods) have been used to collect positional data and integrate it with Geographic Information Systems (GIS). Global Positioning Systems (GPS) is one of the technologies used to establish two and three dimensional (2-D and 3-D) positions that can be utilized to locate point features such as accidents, signs, and intersections, or moving vehicles in real-time (Fekpe et al., 2001). GPS is typically used in differential mode, providing DGPS measurements. DGPS-GIS data integration are part of the innovative advanced technology applied by Intelligent Transportation Systems (ITS) to efficiently assist winter maintenance operations in the decision-making and planning process.

When both DGPS measurements and roadway centerline maps are very accurate, a DGPS data point is associated with the nearest roadway by calculating the minimum perpendicular distance between each roadway centerline and the DGPS data point. This process is called "snapping". Unfortunately, a spatial mismatch occurs when a DGPS data point is snapped to an incorrect roadway centerline due to lack of accuracy in the digital roadway map, the DGPS measurements, or both. This spatial mismatch or map-matching problem results from inadequate DGPS data collection procedures, limits to the basic accuracy of the DGPS unit, limits to the accuracy of the GIS data source, a flawed GIS digital base map, or combinations of them.

The map-matching problem affects positional accuracy when Automatic Vehicle Location (AVL) systems in conjunction with DGPS technology are utilized to monitor, track, or locate vehicles in real-time. These systems track vehicles in 2-D or 3-D, display their locations in 2-D, and relate them to data referenced to a linear dimension. Vehicle trajectories displayed on a digital map do not lie on top of the roadway centerline, which represents the real world, producing map-matching problems. Figure 1 shows that errors in the location of the measured DGPS data point cause an incorrect snap to the nearest road 2 instead of a correct snap to road 1.

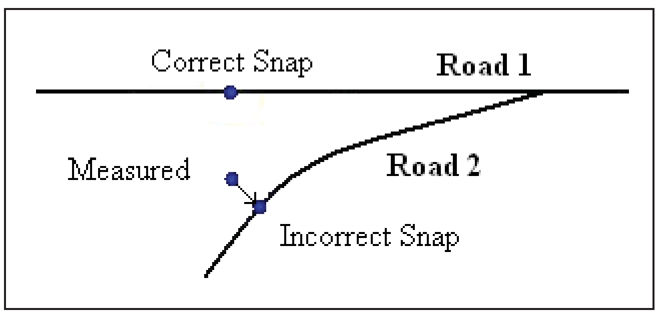

Figure 2: Measured DGPS Data Point Snapped to the Wrong Roadway Centerline

As a consequence of the map-matching problem, the calculated cumulative distance traveled by an intelligent winter maintenance vehicle along a roadway network is incorrect and, therefore, calculated values for winter maintenance performance measures that depend upon cumulative distance are wrong. For example, the quantity of salt spread by a vehicle during a storm event is computed by multiplying the average salt rate by the cumulative distance traveled. Additionally, due to the map-matching problem, non-spatial collected data is associated to incorrect roadways. For example, pavement temperature values collected through sensors are incorrectly assigned to roadways with different pavement type (e.g. bituminous).

Transportation applications such as emergency dispatch systems, real-time highway information, in-vehicle navigation systems, dynamic route guidance, personal navigation assistants, travel speed and delay studies, sign and roadway inventories, congestion and traffic management, collection of roadway grade, travel time studies, locating motor vehicle crashes, transit operations and management, commercial vehicle operations, fleet management, hazardous material management, infrastructure management, incident management, transportation policy analysis, and household travel surveys are in demand of an efficient map-matching algorithm associated with the registration of GPS data points with a digital roadway map (Czerniak, 2002; Fekpe et al, 2001; Quddus et al, 2005). Associating the vehicle location and other collected data with the correct roadway centerline is essential for these applications.

3. LITERATURE REVIEW

The earliest map-matching algorithm followed a semi-deterministic model (French, 1989). This model assumes that the vehicle has an initial location on a roadway and a given direction of travel. A correction is applied whenever the heading of the vehicle changes (Morisue and Ikeda, 1989). However, for this technique to work, the vehicle is generally assumed to follow a predetermined road. There is considerable uncertainty when the vehicle travels off-road because there is no longer any way to correct for errors (Zhao, 1997; Czerniak, 2002).

A probabilistic approach, described later, has the advantage of not assuming that the vehicle is always on a roadway. Vehicle heading error is calculated using an elliptical or rectangular confidence region and error models within which the true vehicle location can be determined. If the vehicle position within the region contains one intersection or road segment, a match is made and the coordinates on the road are used in the next position calculation. As a result, the algorithm yields the best-match segment along with the most probable matching point on the segment (Zhao, 1997; Czerniak, 2002).

White et al (2000) discuss solutions to the map-matching problem for personal navigation assistants. Four different map-matching algorithms were implemented and tested: 1) use of minimum distance (point-to-curve), 2) comparison of heading information with arc and trajectory, 3) use of topology to select roads that are reachable from the current road, and 4) construction of piece-wise linear curves from different paths, followed by comparison of them to centerline curves using points (curve-to-curve matching). The authors concluded that these algorithms worked better when the distance between the GPS point and the closest road was small; and that correct matches tend to occur at greater speeds on straight roadways.

Fuzzy logic is an effective way to deal with tasks that involve qualitative terms and concepts, vagueness, and human intervention. Expert knowledge and experiences employed by a fuzzy-logic-based map-matching algorithm are represented as a set of rules to determine vehicle location (e.g., if the difference between the orientation of the roadway segment and the heading of the vehicle is small, then resemblance between the vehicle travel path and the candidate route is high) (Huang et al, 1991; Zhao, 1997).

There has been abundant research on application of Kalman filters in combination with DGPS and dead-reckoning signals to solve spatial mismatches. This integrated technology improves positioning accuracy by estimating white noise and error in the DGPS and then correcting the vehicle's position (Jo et al, 1996; Mar and Leu, 1996; Sun and Cannon, 1997; Kim et al, 2000; Zhao et al, 2003). Quddus et al (2003) present a general map-matching algorithm that integrates GPS and dead-reckoning sensor data (position, velocity, and time) through an extended Kalman filter and uses them as input to improve performance of the algorithm. The physical location of the vehicle on a roadway link is determined empirically from the weighted averages of two state determinations of the vehicle position based on topological information and external sensors.

Particle filtering, based on a stochastic process, is another approach to the map-matching problem. Particle filters are recursive implementations of Monte Carlo-based statistical signal processing (Gustafsson et al, 2002; Crisan and Doucet, 2002). The authors assert that research is still needed to seek a reliable way to detect divergence and to restart the filter.

Taylor et al (2001) describe an algorithm called “Road Reduction Filter (RRF)” that uses differential corrections and height aids. RRF identifies all possible roadway candidates while systematically removing incorrect ones. RRF is improved by using shortest path network analysis and drive restriction information. A shortest path network routine calculates the distance through the roadway network from a vehicle’s previous position to each potential present position offered by the algorithm. The drive restriction information routine selects roadways using direction and access information.

The map-matching procedure presented by Greenfeld (2002) consists of two algorithms. One algorithm assesses similarity between characteristics of the roadway network and the positioning pattern of the vehicle. The second algorithm performs topological analysis and applies a weighting scheme to match each GPS data point to the roadway network. The highest weighted score determines the most likely candidate for a correct match. The author indicates that further research is needed to determine the most accurate position of the vehicle along a roadway segment and to verify the accuracy performance of the algorithms.

Yang et al (2005) presented a map-matching algorithm that utilizes distance of point-to-curve for relatively long polling time intervals of 2 to 5 minutes. After snapping the GPS point to a node contained within its buffer, the algorithm computes a ratio between the distances of the GPS point to the nearest link and the secondly nearest link, and then compares this ratio to a threshold. Shortest paths to adjacent GPS data points are obtained if the previous process is not successful. According to the authors, additional research is necessary to determine an efficient radius for the buffer and the value of the threshold.

The map-matching algorithms described in the literature review apply procedures with various levels of complexity used to resolve spatial ambiguities. As mentioned by Quddus et al (2003), recent map-matching methods are more inclined to employ roadway network topology to identify correct roadways at complex intersections.

4. PROPOSED DECISION-RULE MAP-MATCHING ALGORITHM

The proposed decision-rule map-matching algorithm resolves spatial ambiguities by determining the correct roadway centerline on which the vehicle is traveling. The algorithm computes shortest paths between snapped DGPS data points using network topology and turn restrictions, as shown in Figure 2 (Blazquez and Vonderohe, 2005). Points 1 and 2 are snapped to ramp 2 because it is the closest roadway contained within the buffers around the points. The shortest path, displayed with a bold arrow, is obtained between the two snapped DGPS data points (S1 and S2). The travel speed between these two snapped DGPS points is determined by calculating the ratio between the length of the shortest path and the difference in time stamps for the points. The computed speed is compared to the average of the speeds at the data points collected by the vehicle while traveling. If the computed speed is within a specified tolerance of the average recorded speed, then the obtained shortest path is viable and the snapped locations for points 1 and 2 are accepted as correct. If a path is not feasible, data points are snapped to alternative roadway centerlines contained within their buffers, shortest paths are recalculated, and speeds are again compared.

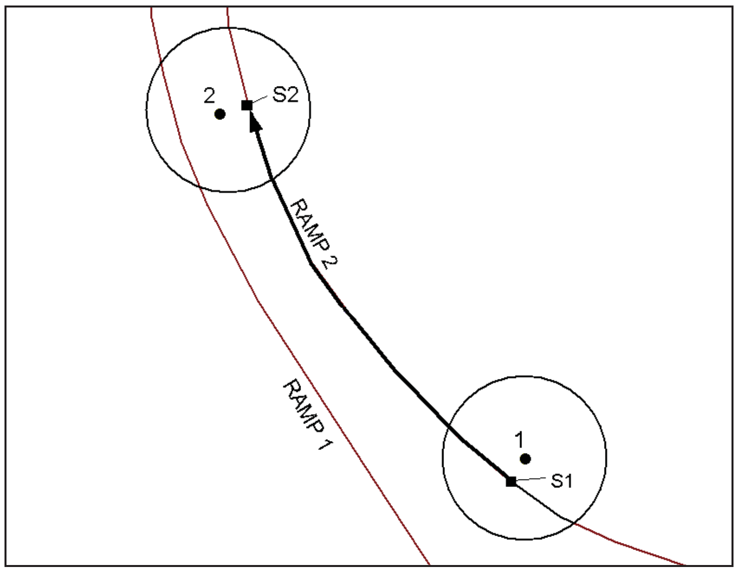

Figure 3: Snapping Process of Two GPS Data Points to the Correct Roadway

If no alternative roadway centerlines exist within the data point buffers, the algorithm advances to the next DGPS data point 3, snaps this point to the closest roadway centerline within its buffer, and calculates the shortest path (2→3) between point S2 and the newly-snapped DGPS data point S3, as shown by the flow chart in Figure 3. If the path between these pair of points is not feasible because the speed comparison yields a large disparity, then the algorithm looks ahead by snapping point 4 to the nearest roadway centerline within its buffer, and determines if the shortest path between snapped points S3 and S4 is possible. If the tested path is also not feasible, then the algorithm snaps point 3 to the next nearest roadway centerline within its buffer obtaining point alt3. The algorithm verifies if a path is feasible between this alternative snapped location for point 3 (alt3), and former and succeeding neighboring snapped points 2 and 4. If these paths are feasible, then the spatial ambiguity is resolved, and the algorithm terminates. However, if the shortest paths between these three snapped points (S2, alt3, and S4) are not feasible because the speed comparison failed, the feasibility of the shortest path between snapped points S2 and S4 is then tested. If this path is not feasible, the algorithm continues by snapping preceding points 2, 1, and 0 one at a time to alternative roadways and determining if feasible paths exist between these newly-snapped points and snapped point 3. Once a feasible path is obtained, the intermediate points are snapped to the roadway along that feasible path. If none of the five consecutive points (0 through 4) used in this example aid in solving the spatial mismatch between the snapped points for points 2 and 3, then it is likely that no roadway centerlines within their buffers yield a feasible path and larger buffers and/or more consecutive data points need to be utilized by the algorithm.

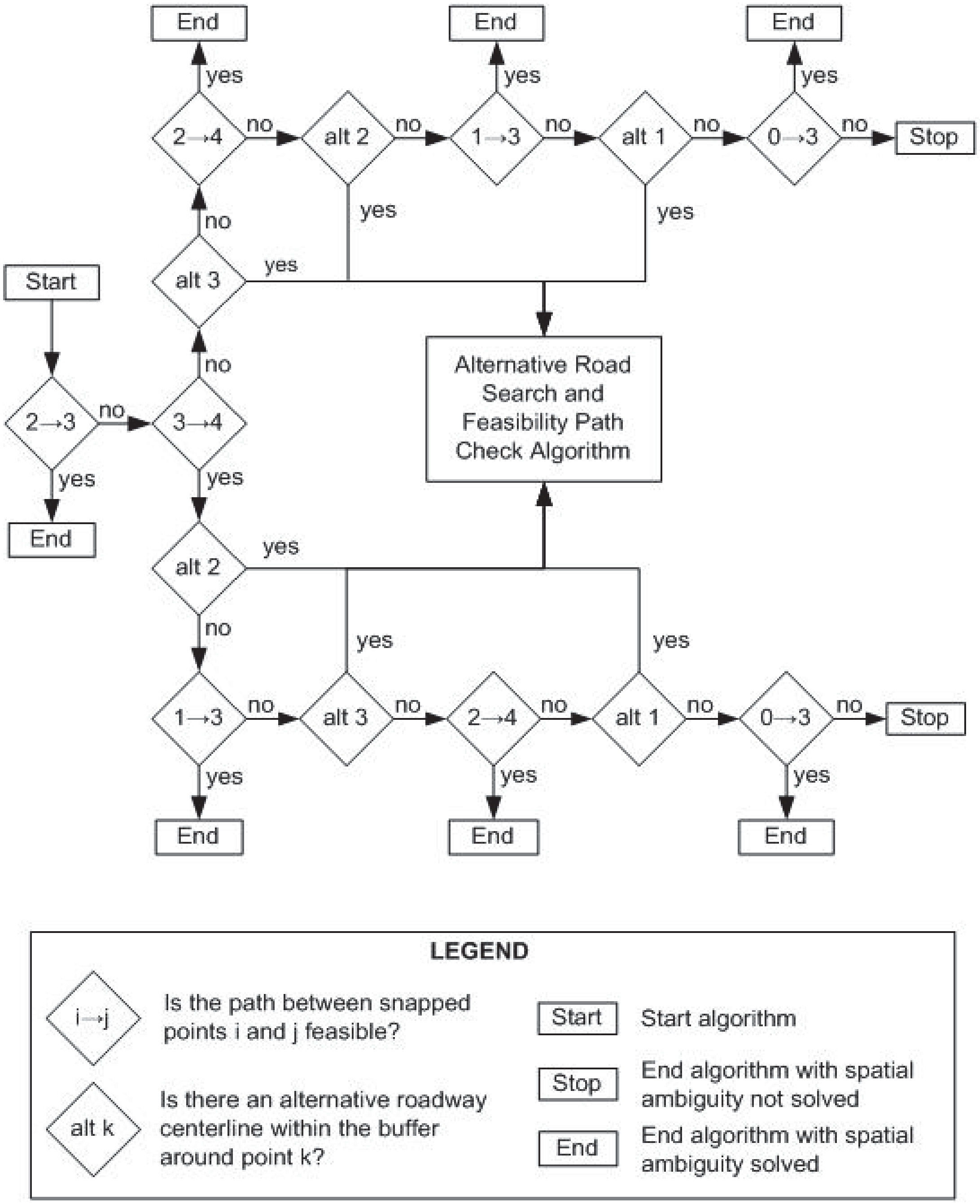

Figure 4: Flow Chart for Decision-Rule Map-Matching Algorithm

5. IMPLEMENTATION OF THE DECISION-RULE MAP-MATCHING ALGORITHM

The decision-rule map-matching algorithm was tested on a set of DGPS data points collected every five seconds by a winter maintenance vehicle during the 2002-2003 winter season in Columbia County, Wisconsin. Columbia County's roadway centerline map has a nominal scale of 1:2,400. Spatial mismatches, occurring at diverging roadways, converging roads, divided highways, and intersections, are resolved by implementing the proposed map-matching algorithm.

Figure 4 presents the results of the algorithm for DGPS data points collected at an interchange in Columbia County, Wisconsin. Points, shown as circles, are the original measured DGPS data points. The incorrect snapping locations for these points are depicted as asterisks, and the correct snapping locations, determined after the algorithm has been executed, are illustrated by rectangles. The lines with bold arrows represent the shortest feasible paths between the correct snapped points. Eleven out of twenty-eight DGPS data points collected by the winter maintenance vehicle at the interchange shown in this figure are snapped to incorrect roadways. If the complete data set (i.e., 600 DGPS data points) collected in Columbia County is examined, 31 data points are incorrectly snapped. All of these spatial mismatches are resolved after implementing the map-matching algorithm. However, spatial ambiguities due to the vehicle traveling against allowable directions of travel or off the represented roadway are not resolved by the algorithm.

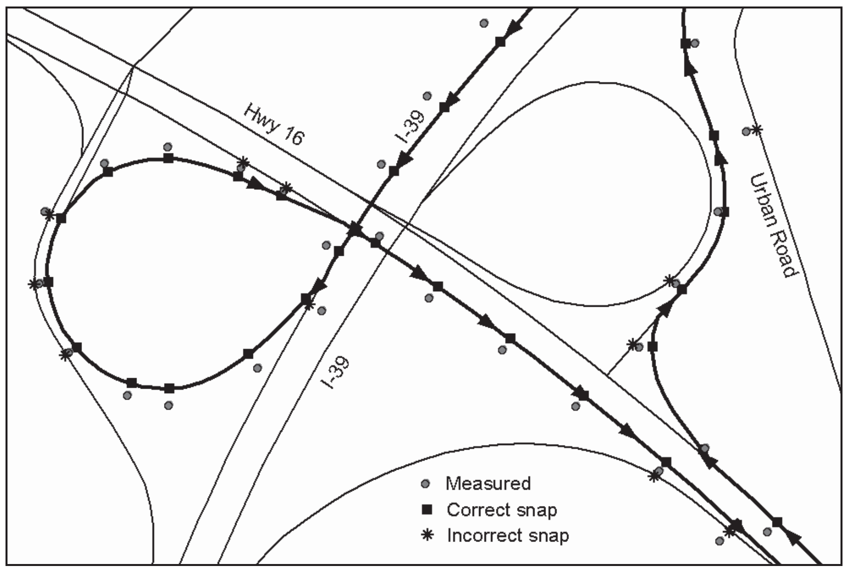

Figure 5: Results of the Decision-Rule Map-Matching Algorithm at an Interchange in Columbia County, Wisconsin.

6. DGPS DATA POINT SNAPPING CASES

Multiple cases (i.e., false negatives, false positives, no solution, incorrect and correct snaps, and solved spatial ambiguities) are obtained from comparing snapping results to the true roadway centerline on which a vehicle is traveling. The true vehicle path is determined by performing a visual examination of the collected data. Data points are classified in these cases before and after applying the map-matching algorithm.

“False negatives” (FN) occur when DGPS data points fail to snap to any roadway centerline when they should have snapped to one. “False positives” (FP) are DGPS data points that snapped to some roadway centerline when they should have not snapped to any centerline. The “no solution” case occurs when DGPS data points do not snap to any roadway centerline because the vehicle is traveling where there is no roadway network represented in the spatial database. If roadway centerlines exist within the buffers of data points, then correct snaps occur when DGPS data points snap to the “true” route of the vehicle. Conversely, incorrect snaps are obtained when

DGPS data points snap to a roadway that is not on the "true" route of the vehicle. Correct and incorrect snaps are computed before and after applying the map-matching algorithm. These are utilized in the study to determine the percentages of solved and not solved cases.

Figure 5 presents the conceptual classification of cases for snapped and not snapped data points before and after applying the map-matching algorithm. The group of data points that does not snap to any roadway contains either FN or points that have no solution. Data points that have roadway centerlines within their buffers are either snapped correctly or incorrectly, or are FP. A data point that snaps incorrectly before applying the algorithm and snaps correctly afterwards is regarded as a solved case. If a data point is snapped incorrectly before applying the algorithm and is snapped incorrectly after applying the algorithm, then the spatial mismatch is not solved. FN, FP, and no solution cases are not included in the solved and not solved case analysis. Notice that the size of the areas shown in this figure does not reflect the percentage of snapped or not snapped DGPS data points.

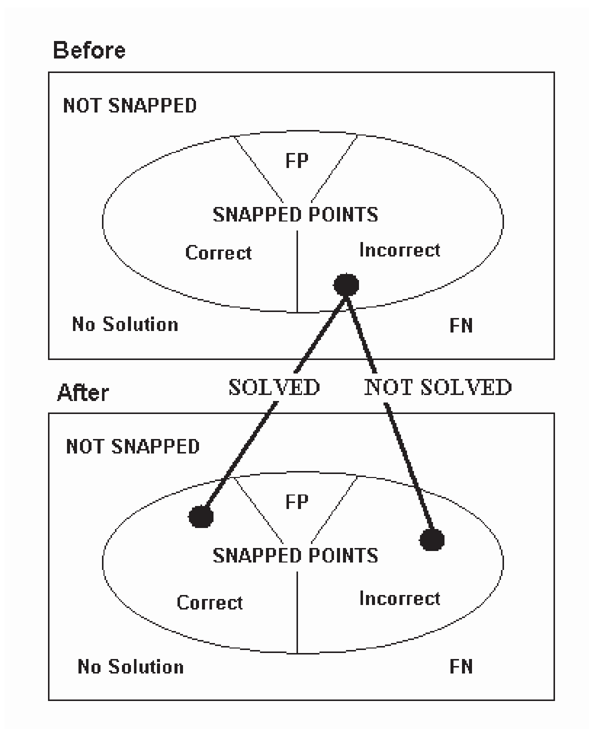

Figure 6: Cases for Data Points Snapped and Not Snapped Before and After Applying the Algorithm

7. CONCLUSIONS AND FUTURE RESEARCH

AVL technology and various additional sensors are used by transportation agencies to collect positional, environmental, equipment status, and material usage data for winter maintenance vehicles in real-time. DGPS data points are associated with roadways by snapping to the nearest centerline in a GIS environment. Spatial ambiguities arise during this association due to errors in DGPS measurements and digital cartography. These can result in DGPS data points being snapped to incorrect roadway centerlines. Such mismatches affect calculation of cumulative distance traveled by the vehicles along a roadway network and assignment of non-spatial collected data to incorrect roadway centerlines, and thus, propagate to the computation of winter maintenance performance measures. Decision-makers utilize these performance measures to evaluate and improve winter maintenance operations.

The proposed decision-rule map-matching algorithm resolves many of these spatial ambiguities by examining the feasibility of paths between pairs of snapped data points. A viable path is the shortest-distance path between two snapped points that a vehicle can travel, while following network topology and turn restrictions, at a speed comparable to its average recorded speed. If a given shortest path is not feasible, then DGPS data points are related to other roadway centerlines within their buffers and new shortest paths are calculated; or adjacent DGPS data points are used to determine feasible paths.

An example is presented to illustrate successful results in solving spatial ambiguities at an interchange in Columbia County, Wisconsin. However, further analysis is necessary to solve spatial mismatches due to the vehicle traveling against allowable directions of travel or off the represented roadway.

Sensitivity analyses for five variables (DGPS positional error, temporal resolution, buffer size, speed range, and number of consecutive data points) are needed to examine the effects of the controlling parameters on the performance of the decision-rule map-matching algorithm. DPGS positional error and temporal resolution are controlled externally through the data, while buffer size, speed range, and number of consecutive data points are parameters of the algorithm controlled by the user. A hypothesis states that there is an increase in the percentage of solved cases as the buffer size, speed range, number of consecutive data points, and temporal resolution increase and as the noise in the DGPS decreases.

Future research should include addressing the following ideas to enhance the performance of the decision-rule map-matching algorithm.

- In addition to collecting coordinate and speed information, vehicle heading data would help solve this type of spatial ambiguity. Vehicle heading and speed comparison can be performed in unison to determine if the snapped DGPS position is feasible.
- Additional research should include addressing cases that involve violation of network topology. There are cases when winter maintenance vehicles travel against allowable traffic directions violating network rules in order to plow snow accumulated along the shoulder of the roadway.

- A dynamic buffer size should be implemented when the algorithm is tempting to solve the map-matching problem. If a path is not feasible and the DGPS data point does not contain an alternative roadway within its buffer, then the algorithm could increase the buffer size until it obtains one.

REFERENCES

Blazquez, C. and A. Vonderohe (2005) Simple Map-Matching Algorithm Applied to Intelligent Winter Maintenance Vehicle Data, Transportation Research Record: **Journal of the Transportation Research Board**, 1935, 68-76.

Crisan, D., and A. Doucet. (2002) A Survey of Convergence Results on Particle Filtering Methods for Practitioners. **IEEE Transactions on Signal Processing**, Vol 50, No 3, 736-746.

Czerniak R. (2002) Collecting, Processing, and Integrating GPS Data into GIS. In Transportation Research Board: NCHRP Synthesis of Highway Practice 301, **Transportation Research Board**, National Research Council, Washington, D.C.

Fekpe, E.S., T. Windholz, K. Beard, and K. Novak (2001). Quality and Accuracy of Positional in Transportation. **In Transportation Research Board: Interim Report National Cooperative Highway Research Program 20-47(01), Transportation Research Board, National Research Council, Washington D.C.**

French, R. (1989) Map Matching Origins, Approaches and Applications. **Proceedings of the Second International Symposium on Land Vehicle Navigation**, 91-116.

Greenfeld, J. S. (2002) Matching GPS Observations to Location on a Digital Map. In Annual Meeting CD-ROM, **Transportation Research Board**, National Research Council, 81st Washington, D.C.

Gustafsson, F., F. Gunnarsson, N. Bergman, U. Forssell, J. Jansson, R. Karlsson, and P. Nordlund. (2002) Particle Filters for Positioning, Navigation, and Tracking. **IEEE Transactions on Signal Processing**, Vol 50, No 2, 425-437.

Huang, L.-J., W.-W. Kao, and H. Oshizawa. (1991) A Fuzzy Logic Based Map-Matching Algorithm for Automotive Navigation Systems, IEEE Roundtable Discussion on Fuzzy and Neural Systems and Vehicle Applications**, Institute of Industrial Science, Tokyo, Japan**

Jo, T., M. Haseyama, and H. Kitajima. (1996) A Map Matching Method with the Innovation of the Kalman Filter. **IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences**, Vol 79-A, No 11

Kim, W., G.-I. Lee, and J.G. Lee. (2000) Efficient Use of Digital Road Map in Various Positioning for ITS. Record **- IEEE PLANS, Position Location and Navigation Symposium**, 170-176.

Mar, J. and J.-H. Leu (1996) Simulations of the Positioning Accuracy of Integrated Vehicular Navigation Systems. **IEE Proceedings: Radar, Sonar and Navigation**, Vol 143, No 2, 121-128.

Quddus, M. A., W. Y.Ochieng, and L. Zhao (2003) A General Map Matching Algorithm for Transportation Telematics Applications. **GPS Solutions**, Vol 7, No 3, 157-167.

Morisue, F. and K. Ikeda (1989) Evaluation of Map-Matching Techniques. **Vehicle Navigation and Information Systems Conference Record**, Toronto, Canada, 23-28.

Sun, H. and E. Cannon. (1997) Reliability analysis of an ITS navigation system. **IEEE Conference on Intelligent Transportation Systems Proceedings**, ITSC, 1040-1046.

Taylor, G., G. Blewitt, D. Steup, S. Corbett, and A. Car. (2001) Road Reduction Filtering for GPS-GIS Navigation. **Transactions in GIS**, Vol 5, No 3, 193-207.

Vonderohe, A., T. Adams, A. Malhotra, G. Stanuch, and C. Blazquez (2002). **Final report Wisconsin winter maintenance concept vehicle: Data management Year 3.** Department of Civil and Environmental Engineering, University of Wisconsin-Madison.

White, C., D. Bernstein, and A. KornHauser. (2000) Some Map Matching Algorithms for Personal Navigation Assistants. **Transportation Research Part C: Emerging Technologies**, Vol 8, No 1, 91-108.

Yang, J-S, S. Kang, and K. Chon (2005) The Map Matching of GPS Data with Relatively Long Polling Time Intervals. **Journal of Eastern Asia Society for Transportation Studies**, Vol 6, 2561-2573.

Zhao, Y. (1997) **Vehicle Location and Navigation Systems.** Artech House, Inc., Norwood, MA, 1997.

Zhao, L., W.Y. Ochieng, M.A. Quddus, and R.B. Noland. (2003) An Extended Kalman Filter Algorithm for Integrating GPS and Low Cost Dead Reckoning System Data for Vehicle Performance and Emissions Monitoring. **The Journal of Navigation**, Vol 56, 257-275.