PHOTOGRAMMETRIC MEASUREMENT OF THE TURNING PATHS OF ARTICULATED VEHICLES

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Commission IV

ABSTRACT

A photogrammetric system has been developed, tested and implemented for documenting turning paths of large articulated vehicles passing through intersections. This information was needed for use in intersection design and traffic regulation to handle the growing national fleet of longer trucks operating on U.S. highways. The necessary data has been obtained from photographs taken using multiple non-metric SLR cameras, wired in series and fired simultaneously. This study has focused on eight different intersections. To obtain a statistically significant sample of data, an average of 80 trucks have been photographed as they proceeded through each intersection. Their paths have been documented using anlaytical photo-triangulation. This paper describes the photogrammetric system that was designed to document the vehicle paths, discusses its implementation, and summarizes results obtained.

INTRODUCTION

The United States Surface Transportation Act of 1982 required states to allow the operation of longer trucks on significant portions of their highway systems. Now there are increasing concerns on how to handle the turning maneuvers of the growing national fleet of these longer trucks, particularly articulated ones. Besides serious traffic safety considerations, there are also maintenance costs for repair or replacement of roadside signals, signs, guardrails and other objects, which are often hit by trucks in the course of turning through these intersections.

Although there has been research conducted on theoretical turning characteristics of long trucks, there has been little done to document actual truck operation through constricted intersections. The Wisconsin Department of Transportation is particularly interested in determining truck paths through selected intersections by methods which would not likely affect driver behavior. This data would be used to supplement theoretical truck turning templates and enable highway designers to more thoroughly consider long truck movements in intersection design. The information would also be useful in analyzing the effects of further legislation which could allow for even longer trucks.

Considering this problem, with its restrictions and complications, it appeared that terrestrial photogrammetry could provide the most economical and best overall solution. This paper describes a system that was designed and tested to solve the problem, and discusses its implementation at eight different Wisconsin intersections, four urban and four rural.

BASIC DESIGN CONSIDERATIONS

The following factors had to be taken into consideration in developing a photogrammetric system suitable to solve the problem at hand:

1) Documentation of the paths of approximately 80 to 100 different trucks, passing through up to 8 different intersections was desired.
2) For purposes of the intended analysis, it was desired that vehicle path positions be correct to within approximately $\pm$ 0.1 foot.
3) To adequately describe the path of any vehicle through an intersection, five documented positions along the turning arc (the end points, plus three intermediate points) were considered necessary.
4) The trajectories of the exterior centers of the vehicle's wheels, and the most extreme corners of the vehicle were considered to be the most important ones for documenting its path through the intersection.
5) To locate these vehicle positions reliably and at the desired accuracy level, the image of each vehicle at each of its five documented positions should be visible on at least three photos taken simultaneously.
6) The intersections could become rather constricted for camera placement, especially in urban situations.
7) The vehicles would be moving, thus all cameras would have to be fired simultaneously from some remote observation point.
8) If the front and rear vehicle widths and track widths could be established, it would only be necessary to determine wheel and vehicle corner locations on one side of the vehicle to define the vehicle's intersection "passage envelope", or area occupied by a vehicle as it passes through an intersection (see Figure 3).
9) To achieve the above objectives under the given constraints, at least three, but ideally more, cameras would be required.
10) The cameras would have to be relatively inexpensive and capable of remote firing.
11) In photographing up to 100 vehicles passing through an intersection, using at least 3 cameras simultaneously, and taking 5 positions of each vehicle in its turn with each camera, up to 1500 or more different, yet related photos would be taken at any given intersection. Considering that 8 different intersections were to be studied, this yields a total of 12,000 or more photos. Clearly the cameras would have to have automatic incremental photo numbering systems, and utilize relatively inexpensive photographic materials.
12) Recognizing the large number of photos to be processed, the mensuration system would have to enable rapid, efficient photo coordinate measurement with automatic and simultaneous storage of the data files in a computer so that they would be readily available for subsequent processing.

SYSTEM HARDWARE

In consideration of the above factors, a system was adopted which utilized motor driven 35mm single-lens-reflex cameras. Canon T-70 cameras were selected because they could be obtained with remote switches. Thus multiple cameras could be wired in series and fired simultaneously by one operator pressing a single switch. Command backs were also purchased for the cameras which enabled identification numbers to be automatically incremented and imaged on each photo. The cameras were equipped with lenses having 28 mm focal lengths, as this provided a relatively wide field of view.

For measuring the photo coordinates, a special apparatus was designed. This device, which has been described in detail in an earlier paper,[1] utilizes a surplus Multiplex stereoplotter projector, and a 22-inch square tablet digitizer interfaced with an IBM PC microcomputer. Negatives to be measured are projected onto the tablet digitizer, and enlarged approximately 14 times in the process. The system must be operated in a darkroom, and to enable measuring under these darkened conditions, a special cursor has been designed. It consists of a reflecting platen with a tiny speck of light in the center which serves as the reference mark for making precise measurements. The light speck is transmitted to the platen by means of a fibre optic. The projector has been modified to enable 35mm films to be entered on rolls for ease of handling.

The device has been carefully calibrated for its systematic errors by making repeated measurements of a precise grid. Corrections for this calibration are made through the application of polynomials. Tests have been conducted which indicate that the device can consistently yield photo coordinate measurements, at negative scale, with errors in the range of under 10 micrometers.

This device enables photo coordinate measurements to be made very rapidly and conveniently, and because the entire image is projected and visible on the digitizer, very few mistakes occur in point identification. Output files consisting of photo coordinates are created directly in the computer where they are readily available for subsequent use in the analytical solution.

SYSTEM SOFTWARE

The computing process used in this project utilizes a number of sub-programs, or modules, with the data processing passing from one module to the next. The functions of these modules are described below, in the

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[1] Montgomery, S.B. and P.R. Wolf, "Mensuration System for Small Format, Non-Metric Analytical Photogrammetric Applications", Technical Papers, Vol. 4, 1986 Annual Convention of The American Society for Photogrammetry and Remote Sensing, Washington, D.C., 1986.

order in which they are performed.

SOFTSURV[2] - Performs least squares adjustment of the distances and angles measured in the field to locate the approximate positions of camera stations and obtain precise coordinates of photo control points.

REFINE - Creates files of digitized photo coordinates and performs corrections for systematic errors of the digitizer.

PREPRO - Performs necessary preprocessing for entry of data into a self-calibrating bundle adjustment program. Its functions include sorting to create ordered files of photo coordinates, and ground coordinates; applying preliminary corrections for camera calibration; and performing resections to obtain initial approximations for the camera station coordinates and orientation angles, and intersections to obtain initial approximations for the unknown vehicle points.

SELCAL[3] - Performs a simultaneous photogrammetric bundle adjustment. It incorporates camera self-calibration, and enables observed spatial distances and angles to be input as control, in addition to the traditional X, Y and Z coordinates of control points. The program has been modified to permit it to be operated on an IBM PC AT computer.

TDIM - Computes dimensions on turning vehicles, including their lengths and widths, from adjusted coordinates of truck points. These are useful for plotting the trucks in their turning paths, and for checking purposes.

TEST PROJECT

Prior to employing the photogrammetric system at the actual selected intersections, a preliminary test was conducted in an open area, in which a simple right angled intersection was simulated. As shown in Figure 1, three camera stations were established in positions that would ensure that a test vehicle travelling in a turning arc would be visible at all times from each station. Five traffic cones and six range poles, held vertically in tripods, were placed within the fields of view of the cameras to serve as control. Their positions relative to the camera stations were carefully determined by measuring angles and distances, and

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[2] This program was created by Charles D. Ghilani of the University of Wisconsin-Madison.

[3] This is a modified version of the program, "Simultaneous Multiple Camera and Multiple Focal Setting Self-Calibrating Adjustment" developed by Clive S. Fraser of Geodetic Services, Inc.

adjusted using the method of least squares.

A small truck, which served as a test vehicle, was driven along an arc simulating travel through an intersection. As it moved, the vehicle was photographed at five points; near the beginning and ends of its arc, plus three additional intermediate locations. To increase the horizontal fields of view of the cameras, they were rotated in kappa so that the horizon coincided approximately with a format diagonal. This increased the field of view by nearly 10 degrees, making it approximately 75 degrees.

As the vehicle travelled around its arc, a person leaning out from the back tailgate used a can of yellow spray paint to carefully mark, on the ground, the travel path of the outside edge of the right rear wheel. The test was repeated several times. Using multiple distance measurements from the control points, locations of five points, uniformly spaced along this yellow arc, were measured. These were also included in the least squares adjustment, and thus produced coordinate positions along the arc to be used for comparison with photogrammetrically derived positions.

Using the previously described mensuration system, photo coordinates of vehicle points that appeared on the photos were measured. The data was processed to compute the coordinates of the five wheel points on the arc using a preliminary version of a simultaneous bundle adjustment which did not include self-calibration. A very large scale plot of the vehicle's arc was made from the five photogrammetrically determined points. On the same diagram, the arc from the five surveyed points along the yellow paint line were plotted. A comparison between the two arcs showed that they

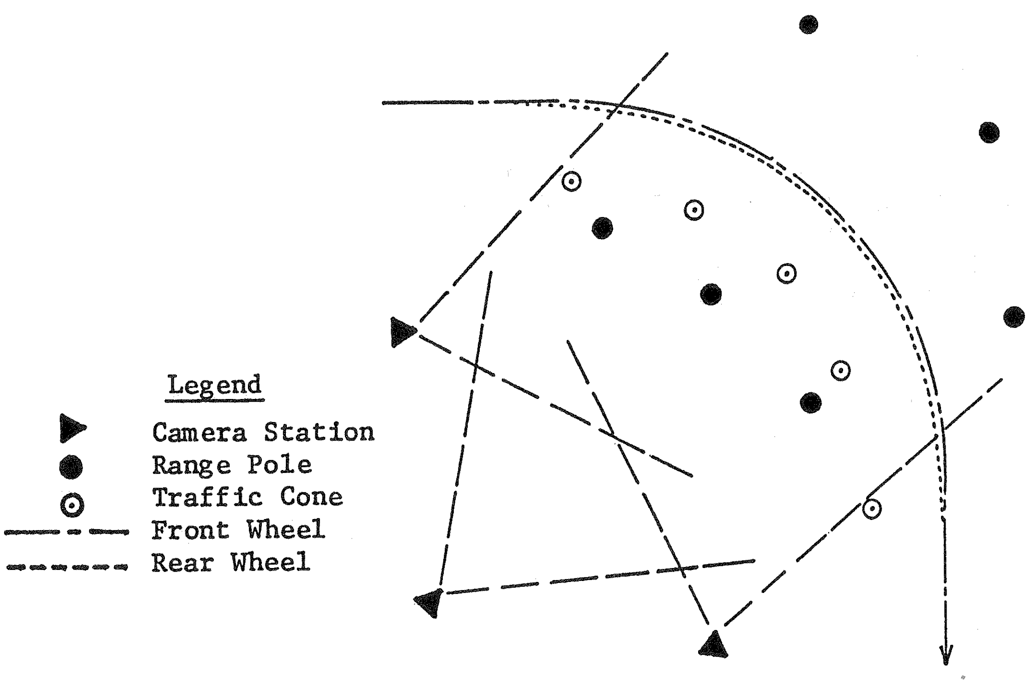


Figure 1. Field Configuration for Test Project.

agreed very closely, and the desired accuracy level of ± 0.1 foot appeared to be met. Other checks were also made. For example the truck's wheelbase (distance between front and rear axles) was measured with a tape. This distance was also repeatedly computed photogrammetrically, and agreed to within a root mean square value of ± 0.06 ft. of the directly measured value.

As noted above, this was a preliminary project. It did not use a self-calibrating bundle adjustment, and the cameras had no fiducial marks. The corners of the format were used as fiducials, and the indicated principal point at the intersection of diagonals was taken as the principal point. Calibrated focal lengths and radial lens distortion values were determined in a separate field calibration procedure, and used in this adjustment. The results obtained on the test project were nevertheless encouraging enough to enable proceeding to the actual problem. However, in the meantime fiducials were installed in the cameras and they were carefully re-calibrated to obtain fiducial coordinates, offsets to the principal point from the indicated principal point, calibrated focal lengths, and radial lens distortion characteristics. This data served as input to the self-calibrating bundle adjustment used later. The fiducial marks that were installed were simply small thin square pieces of opaque plastic which were fastened at the four corners of the format using super glue. These have proved to be stable and durable, and have worked very well.

SYSTEM IMPLEMENTATION

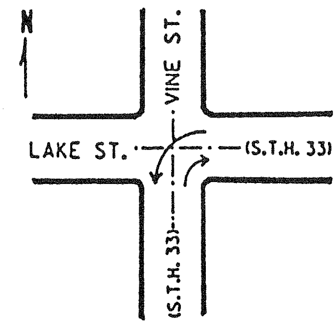
Having successfully completed the test project, the photogrammetric system was implemented to study the passage of articulated vehicles through actual intersections. The eight intersections illustrated in Figure 2 were studied. These intersections, all located in southern Wisconsin, were chosen because they presented a variety of conditions, including:

1) Urban and rural settings
2) Federal, state and local highways
3) Varying angles between intersecting highways
4) Left and right turns
5) Two and four lane highways
6) Other varying factors including grades, signing, signaling and parking conditions.

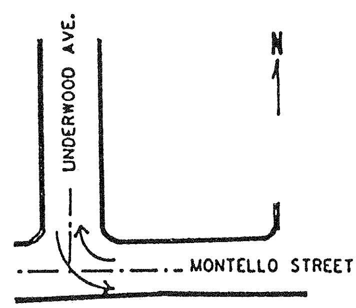
To ensure that enough trucks would pass through each intersection to produce a statistically significant sample, vehicle counts were taken beforehand. Each intersection was also studied prior to actual photography to assess its overall geometric configuration, plan the locations of camera stations, identify existing objects that could serve as control points, and plan additional control if needed.

Factors that were considered in designing the photogrammetric plan for each intersection were:

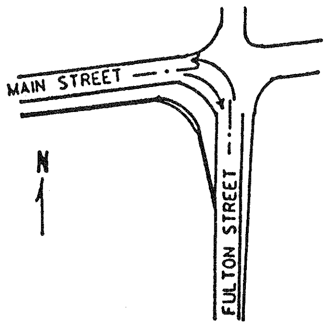
1) The cameras could not interfere with normal traffic flow.



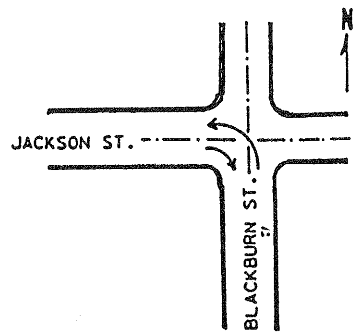
Site 1. Horicon (Urban)



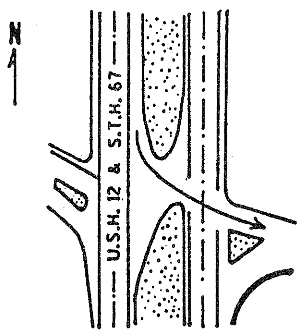
Site 2. Montello (Urban)



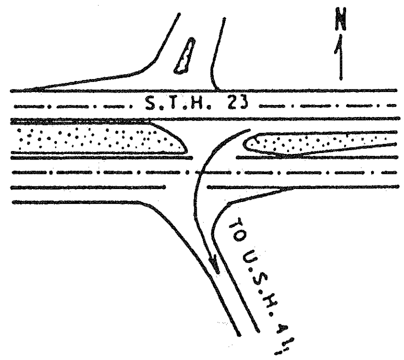
Site 3. Princeton (Urban)



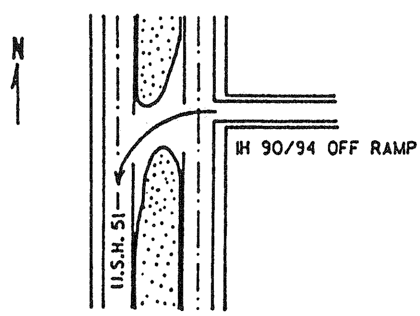
Site 4. Ripon (Urban)



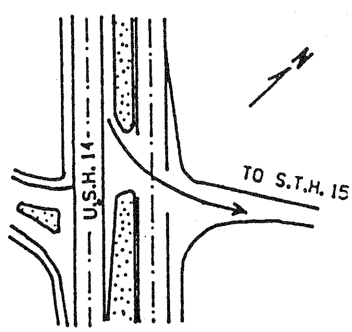
Site 5. Elkhorn (Rural)



Site 6. Fond Du Lac (Rural)



Site 7. Madison (Rural)



Site 8. Darien (Rural)

Figure 2. Eight Wisconsin Intersections Selected for the Study.

2) Camera placement had to enable convenient wiring in series so that simultaneous firing could be accomplished by an operator at one good observation point.
3) The cameras had to be readily accessible for changing film, which was necessary after photographing 7 trucks.
4) Each truck should be within the field of view of at least 3 cameras at all positions in its turning arc.
5) The strongest possible geometry of intersecting rays was desirable.
6) An overall good geometric configuration of control within the photos was essential, and for space resection to obtain initial approximations, at least 3 control points should be imaged in each photograph.
7) Truck dimensions as well as their paths were important in this study. Therefore camera placement had to ensure that several "critical" points were located for each truck position. These included the four extreme vehicle corners, the outer front wheel, and the inner rear wheel. This could be achieved most conveniently by placing all cameras on the outside of the turn, however the front and rear of the truck had to be imaged on three photos at the start and end of its turn to enable calculating the truck widths.

Figure 3 illustrates one of the intersections studied, a right angled one in the City of Horicon, Wisconsin. This is an area of heavy truck traffic, due in part to a variety of industry in and around the area. As shown in the Figure, this is a very constricted intersection. To enable photographing vehicles throughout their turning arcs, and meet the earlier stated conditions, six camera stations were necessary for this particular intersection. Several control points were selected which appeared in the fields of view of the photos. These were unique points on buildings, street signs, poles, etc. in the area. Positions of these and the camera stations were determined by multiple measurements of angles and distances, followed by least squares adjustment.

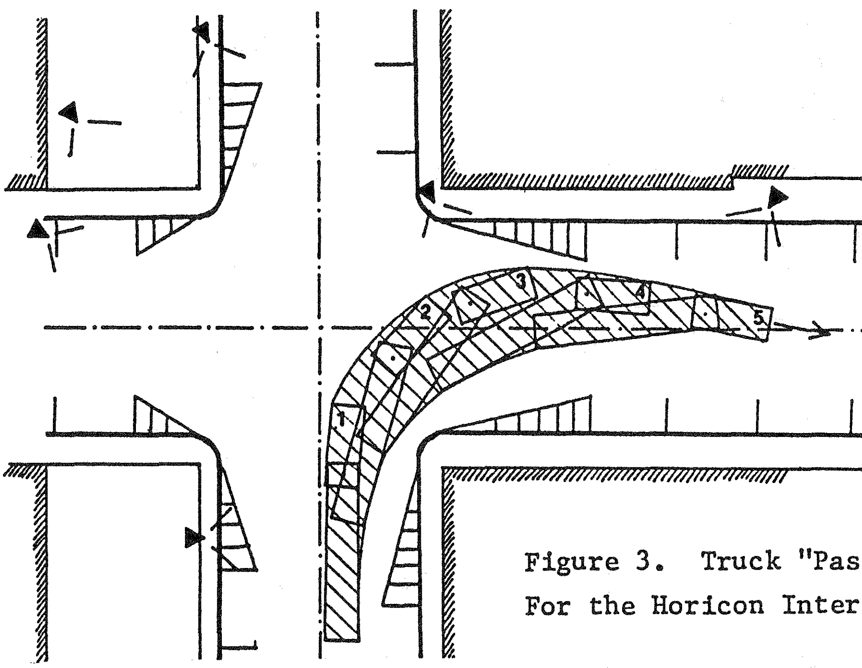


Figure 3. Truck "Passage Envelope" For the Horicon Intersection.

The Horicon intersection of Figure 3 is representative of problems encountered with urban intersections, although because of the space constrictions caused by stores, as previously noted 6 cameras were used. Five cameras were used on all other intersections. The rural intersections were more open which eased camera placement. However, rural intersections were less favorable from the standpoint of control, with fewer existing points available. In most cases, artifical control points had to be added to fill in areas void of existing features.

In digitizing the photo coordinates, numerous points were measured on each of the trucks. This enabled locating the "critical" points, and also yielded other points to be used for purposes of obtaining checks. To provide uniformity and avoid confusion, the point identification and numbering scheme illustrated in Figure 4 was adopted.

The files of measured photo coordinates created during digitizing were processed through the previously described self-calibrating bundle adjustment program. In the reduction process, only three images were used and the ones selected were those which produced the best geometry of intersections. This was done to reduce the number of measurements needed and speed the process of measuring such a large number of photos. Results, to be discussed later, showed that sufficient accuracy was obtained by using only 3 intersections.

Plots of the travel paths of the vehicles through the intersections were developed from the solutions. Figure 3 shows a rendition of one vehicle passing through the Horicon intersection. The vehicle's passage envelope is shown crosshatched. Note that vehicle widths were computed photogrammetrically, and this enabled plotting the entire vehicle and its passage envelope. Figure 5 shows the traces of the critical corners - outside front and inside rear - for a number of trucks passing through the Horicon intersection. Note the long (approximately 100 feet) encroachment of up to 15 feet into the opposing lane for the outside front corner, and travel out of the street and over the curb for the inside rear wheel.

DISCUSSION OF RESULTS

For the eight intersections studied, it was of course not possible to make direct measurements with which to assess accuracies as had been done in the test. However, statistical analyses and other checks were made. For each intersection, a large representative sampling of data produced root mean square standard deviations in computed X, Y and Z object coordinates. These were most consistently in the range of about ± 0.05 ft., but in the worst cases they were in the range of only ± 0.15 ft.

Root mean square photo coordinate residuals obtained from the bundle adjustment for the eight intersections were quite consistently within the range about ± 15 micrometers. In fact, these residuals were often within about ± 10 micrometers, they rarely exceeded 25 micrometers, and a very few, which were rejected from the solution, were larger than 50 micrometers.

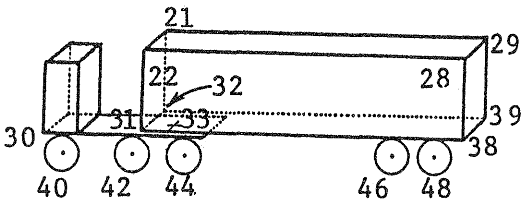


Figure 4. Truck Point Numbering Scheme.

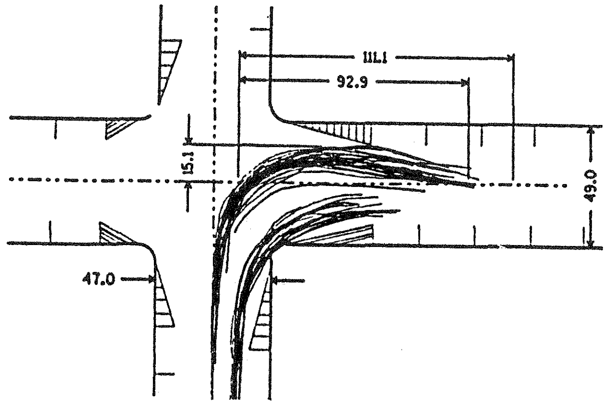


Figure 5. Traces of Critical Corners for Trucks Turning Through Intersection.

As another check on the quality of the results, multiple calculations of lengths on the trucks could be made. For example, any trailer length could be calculated by an inverse from computed coordinates of points 22 and 28 of Figure 4. This calculation could be repeated for each position where that particular truck was photographed within its turning arc. Since the length is constant, comparisons could be made to determine the consistency with which these constant values could be repeated through photogrammetric calculations. These types of comparisons consistently yielded root mean square checks within approximately ± 0.10 ft.

SUMMARY

This research adds to a growing list of examples which demonstrate how valuable terrestrial photogrammetry can be in the solution of unique and otherwise difficult measurement problems. In this instance a dynamic measurement problem has been solved in an environment consisting of busy highway intersections where direct measurements would be dangerous if not impossible. In this situation it was considered important to record natural driver behavior, and it is believed that this was achieved. The data obtained in this study should be of significant value in future intersection design and traffic regulation at intersections.

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