7TH WCTR
SYDNEY AUSTRALIA
1995

TOPIC 12
GIS, LAND INFORMATION
SYSTEMS AND DATABASES

AN ENHANCED MATCHING ALGORITHM FOR NUMBER PLATE SURVEYS

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Abstract

Origin-destination number plate surveys are commonly used to investigate vehicle routes and travel times. This paper reviews some present methods for matching number plate data, and describes the development of an improved matching algorithm. The algorithm considers vehicle speeds, types, routes, the survey layout and possible errors in transcription.

INTRODUCTION

Origin-destination (OD) number plate surveys are a common traffic survey method used to investigate vehicle routes, travel times and volumes. Data from OD surveys are often used to forecast demand on new traffic links and to predict the effects of other changes to the road network.

The results from an OD survey should ideally give an accurate description of vehicle volumes using various routes through an area of the road network. Unfortunately the capacity for error is high, particularly in large-scale OD surveys. Errors arise during both data collection and analysis of the survey.

Error correction can be a somewhat arbitrary process. Research has been conducted by Makowski and Sinha (1976), Hauer (1979), Shewey (1983) and Maher (1985) to devise statistical methods of error correction, however there presently appears to be little consensus in the traffic engineering profession as to which methods give the best results.

It is difficult to estimate the magnitude of errors in a number plate survey, since there is generally no "perfect" survey as a comparison. It is, however, possible to reduce the magnitude of errors by improving data collection and analysis techniques. This paper proposes an improved technique for reducing analysis errors.

ORIGIN-DESTINATION SURVEYS

An OD number plate survey is conducted by first selecting an area of the transport network to study (the study area). Observation stations are set up on all (or most) roads entering and leaving the study area, forming an external cordon. A number of internal observation stations are usually established inside the area as well.

Observers at each station record the time, number plate and direction of each vehicle in the survey sample that passes through the station. The survey sample may be all vehicles or may be a selection, for example all trucks, all red vehicles, or all vehicles with number plates ending in '1'. Depending on the purpose of the study, data would usually be collected on a fairly representative day of travel, such as a normal working weekday.

After data collection, all occurrences of each number plate are matched to determine the routes travelled by each vehicle. A computer software package is generally used to enter the data from the survey and to match number plates. Matching is best illustrated by an example :

Assume number plates have the format of three letters followed by three digits. Say a number plate, ABC123, is observed at station 1 at 9:00 am (see Figure 1). If ABC123 is then observed at station 2 at 9:05 am and station 3 at 9:15 am, then it could be inferred that a single vehicle had passed along the route shown.

After all observations have been matched, trip information is summarised in an OD matrix showing all station-to-station flows. Vehicle paths may also be plotted as desire lines on a map of the study area.

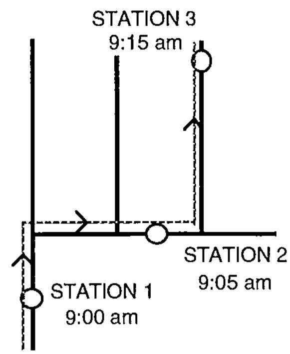

Figure 1 **A sample match**

ERROR CONTROL IN ORIGIN-DESTINATION SURVEYS

Data collection errors

Most errors in number plate surveys occur in the field. Observers may miss vehicles all together, transcribe number plate characters incorrectly (for example, mistaking the letter 'I' for the numeral '1') or mistake a vehicle's classification. Unreadable handwriting or unclear tape-recording may also result in erroneous or unusable data.

When field data is entered into a computer, typing mistakes will occur. The extent of data entry error is dependent on the experience of the operator, the method of data entry and the number of people entering the data.

Adjustments are usually made for missed observations and data entry errors after the survey. Schaefer (1988) has described a simple 'method of moments' technique to compensate for data collection errors by factoring up the number of matches.

Spurious matches

A common practice in number plate surveys is to record only part of each vehicle's number plate. Partial recording makes observations quicker and reduces the total volume of data collected. The main disadvantage with this method, however, is that spurious matching may occur during analysis.

A spurious match occurs when:

- two vehicles that have identical partial number plates are simultaneously present in the study area; and
- the two vehicles are matched as being one vehicle.

For example: if the last four characters of each number plate are recorded, the number plates AB*C123* and BQ*C123* would be treated as the same vehicle if they form a plausible trip.

Makowski and Sinha (1976) have suggested a simple statistical approach for estimating the number of spurious matches between two stations. Hauer (1979) found their reasoning to be slightly incorrect and proposed a new heuristic formula. Using Hauer's formulation, spurious matches for partial number plates of one letter and three digits would amount to less than 10% of all matches at a single pair of stations.

Shewey (1983) applied Hauer's estimates to number plate surveys carried out in the UK and found that in some cases the estimates were unacceptably high. Shewey proposed a matching algorithm that took into account the travel time between a pair of stations. The algorithm aimed to improve accuracy during matching, rather than adjusting the number of matches afterwards.

Two years after Shewey's paper, Maher (1985) proposed two further statistical methods based on least squares and maximum likelihood estimates. Maher's approach was similar to Hauer's in that he made adjustments after matching. Maher, however, extended his analysis to the case of more than two observation stations.

At present there does not appear to be an ideal method for eliminating or compensating for spurious matches. The following section describes a detailed algorithmic approach for reducing the extent of spurious matching in OD surveys.

AN IMPROVED MATCHING ALGORITHM FOR OD NUMBER PLATE SURVEYS

Rationale

The error-correction methods discussed earlier are statistical in their approach. In all of the methods, except Shewey's technique, predicted error adjustments are made *after* the matching process. Shewey's technique, on the other hand, attempts to correct potential errors *during* matching. Shewey reasons that it is better to correct for spurious matches at the source, rather than to compensate for them afterwards (Shewey 1983). The following discussion concentrates on the development of an algorithm using this latter approach of attempting to ensure all matches are genuine.

In the error correction methods of the previous section, very little use was made of all the information usually available in a number plate survey. Most number plate surveys will record data not only for number plates and observation times, but also vehicle classifications, vehicle directions and the spatial relationships between observation stations. The accuracy of a matching algorithm is expected to improve as more information is used in deciding whether or not a match is genuine.

Outline of the algorithm

The improved number plate matching algorithm uses a range of criteria for evaluating the authenticity of a match between a given pair of stations. These include:

- the vehicle's speed
- the vehicle type (eg car, articulated truck, bus)
- the vehicle's route
- the vehicle's time of travel and the size of the study area
- the average distance between observation stations (local density)

Each of the criteria is evaluated to determine a numerical weighting for the match. If the weighting is above a predetermined threshold, the proposed match will be deemed an eligible candidate. After all possible matches have been analysed in this way, the candidate with the highest weighting will be accepted as the true match. The matched observation is appended to the end of the vehicle's trip and becomes the new point of comparison for all matches in the subsequent leg of the trip.

A flowchart showing the algorithm outline is given in Figure 2.

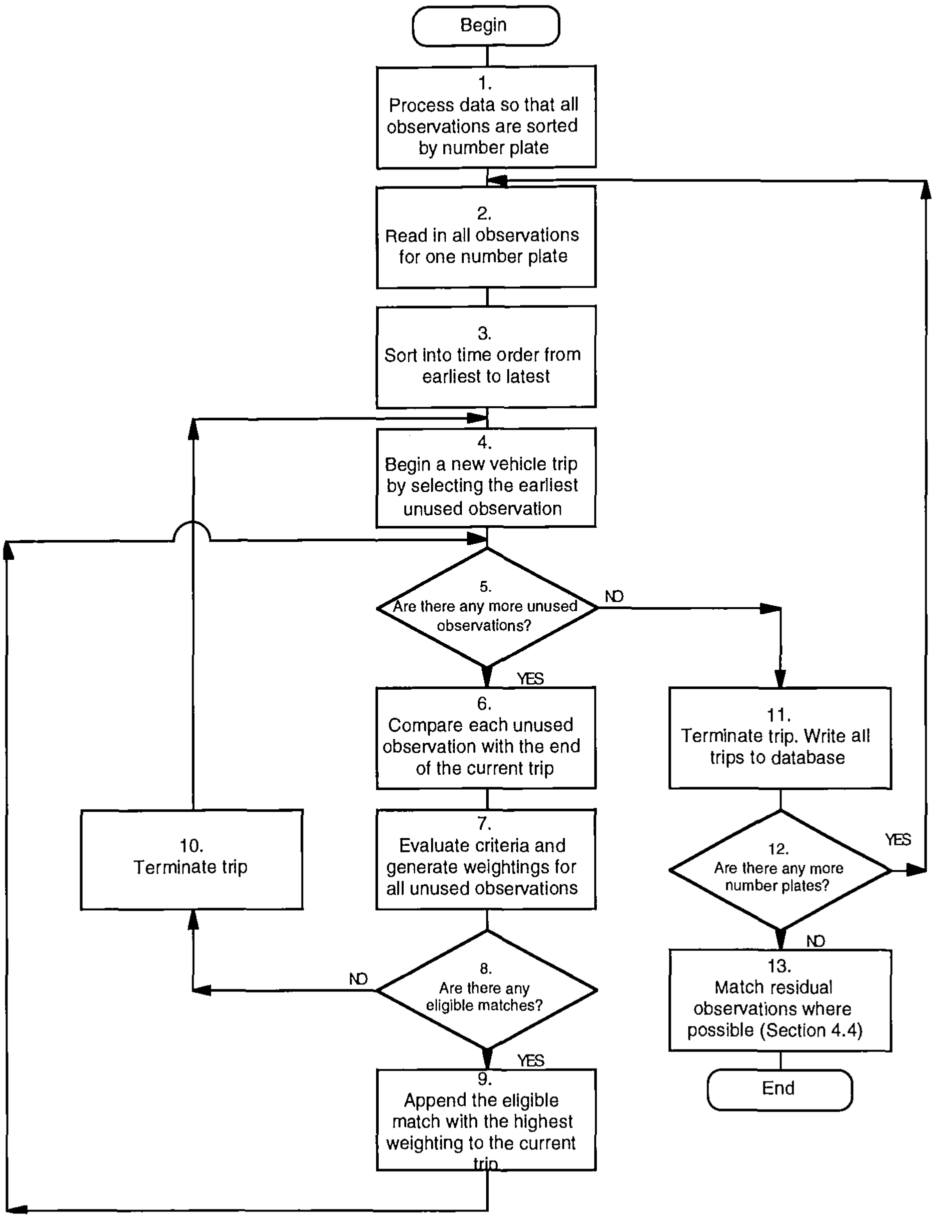

Figure 2 Outline of matching algorithm

Matching criteria

Travel time

Time is the fundamental consideration in deciding whether or not a match is genuine. It was empirically found using the programs described in the next section that the most likely match for the end of a trip is usually the next observation in chronological sequence. Candidate matches that have shorter travel times are therefore given a higher weighting, increasing their chances of being chosen.

The algorithm uses the following linear interpolation formula to assign initial weightings to the candidate matches.

$$w = w_{max} - \frac{t}{t_t}(w_{max} - w_t) \qquad (1)$$

where:

w = assigned weighting

t = travel time between stations

t_t = traversal time (see below)

w_{max} = a predefined maximum weighting

w_t = user-defined threshold weighting

The traversal time (t_t) is a rough estimate of the maximum time a through vehicle will take to cross the study area from one side to another. It gives a measure of the size of the study area and assists in deciding whether travel times are plausible. Vehicles crossing a large study area (with a correspondingly large value of t_t) would be expected to have trips of longer duration than vehicles crossing a small study area.

The traversal time may be simply estimated by finding the longest path through the area that does not double back on itself, applying a low average speed and calculating the time of travel by dividing the path length by the speed.

The maximum possible weighting, w_{max}, is an arbitrary upper limit for the weighting assigned to each match. It is convenient to set it to 1.0 so that all weightings fall in the range 0 to 1.0.

The threshold weighting, w_t, is a user-defined proportion of w_{max}. If a candidate match has a weighting that drops below w_t, then it cannot be considered a valid match.

Now that an initial weighting has been derived for each candidate match, the matches are tested with each matching criterion (ie speed, local density, route and vehicle type). If a candidate fails to meet a criterion, the candidate's weighting is reduced by multiplying the weighting by a penalty factor between 0 and 1. Once a candidate's weighting falls below the threshold w_t, it is deemed ineligible for a match. After all criteria have been applied, the candidate with the highest weighting greater than w_t is chosen as the correct match. If no candidate has a weighting greater than w_t, then the vehicle's trip will terminate and a new trip will begin with the next observation in chronological sequence.

Speed

The average speed of a vehicle travelling between two stations is calculated as the on-road distance between the stations divided by the travel time. The algorithm compares the average speed of the vehicle with a low-speed threshold. If the speed is below this threshold, a penalty factor (between 0 and 1) set by the user is multiplied by the current weighting of the match.

In practice an upper speed threshold is of limited use, since vehicle travel times may be rounded to zero. As the travel time approaches zero, the speed will approach infinity. The algorithm therefore allows for apparent high speeds, even though they are not representative of the vehicle's true speed.

How is the travel time rounded to zero? In most number plate surveys, observation times are recorded to the nearest convenient time interval (the time resolution of the survey). A survey of short duration, for example, may record all times to the nearest minute, while a large survey may have a time resolution of five or ten minutes. If two observation stations are quite close together and a vehicle travels between them in a time less than the time resolution, then the travel time calculated will often be zero.

Local density

Speed is a necessary but not sufficient criterion to determine the likelihood of a match where the spatial relationship between observations is considered. For example, consider the situation shown in Figure 3.

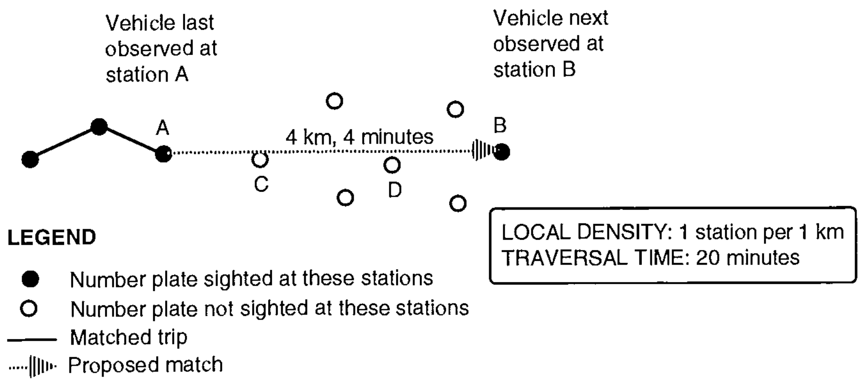

Figure 3 A violation of the local density criterion

The vehicle's speed along leg AB would be 60 km/h—a reasonable speed in an urban area. The travel time of four minutes is also reasonable, being considerably less than the traversal time of 20 minutes. However, the spacing of stations around the locality of the proposed match suggest that the vehicle should have been sighted at one or more stations between points A and B (for example, stations C and D), if it did in fact travel from A to B.

The local density is a term defined in this paper as the average spacing of stations in the locality of the proposed match. The local nature is important, since a study area will not necessarily have a uniform scatter of stations. Although not being a density in the true sense of the word, it is convenient to express the local density in terms of the average distance between stations, for example "one station per 2.5 km", or more simply "2.5 km".

An effective method for calculating the local density has been developed by the author (McPherson 1994). This method, however, is by no means the only way to find the average station spacing, and the reader is encouraged to use any technique that gives a reasonably accurate measure of local density.

The matching algorithm compares the distance between stations with the local density. If the distance is greater than the local density multiplied by a threshold factor, then the current weighting for the match is multiplied by a penalty factor set by the user.

For example, if the threshold factor is 1.5, local density is 2.0 km, and the distance between stations is 4.0 km, then the following comparison is performed:

4.0 km > 1.5 x 2.0 km

therefore a penalty factor is applied to the weighting. In practice it is wise to set the threshold factor greater than 1.0 to allow for possible missed observations at nearby stations, and for irregularities in station distribution.

Route

As well as temporal and spatial criteria for the match, a logical criterion is needed. Is the vehicle's route reasonable?

To assess this criterion thoroughly, prior knowledge of common vehicle routes is necessary. Here a dilemma arises, for the main purpose of an OD survey is to acquire such information; we require the final results from the survey in order to analyse the data from the survey.

One possible approach is to iterate the analysis, so that one or more passes through the data are used to generate probabilities of vehicles travelling between each pair of stations. In each iteration, probabilities from the previous iteration are used to modify the weighting assigned to each potential match. Unfortunately this process may be prohibitively slow, particularly for large OD surveys.

A less sophisticated approach, which is quicker but less accurate, is to examine the geometric characteristics of a vehicle's trip. If a vehicle appears to double back on itself, then the probability of a match is decreased. The algorithm implementation in the next section uses this doubling-back criterion rather than the iterative generation of route probabilities.

There are two cases where a vehicle will be regarded as having doubled back on itself (Figure 4).

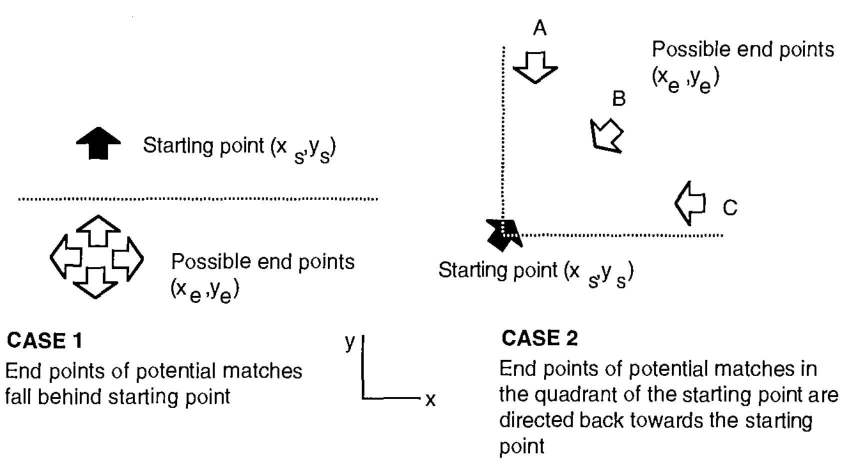

Figure 4 Violation of the route criterion (doubling back)

The algorithm evaluates the cases by comparing directions and station co-ordinates. For case 1 in Figure 4 (north starting direction), let

$$\Delta x = x_e - x_s \tag{2a}$$

$$\Delta y = y_e - y_s \tag{2b}$$

Since the starting direction is in the direction of positive Δy, then all observations that have negative Δy will have doubled back and failed the route criterion.

For case 2 (north-east starting direction), all observations in the north-east quadrant are tested with the route criterion. Observations that have directions exactly opposite to the starting direction (for example, observation B in Figure 4) automatically fail the criterion. If the observation is close to the north-south boundary of the quadrant, then south-pointing observations are regarded as route violations (observation A). Similarly, west-pointing observations close to the east-west quadrant boundary will violate the criterion.

An observation is "close" to the north-south boundary if the absolute value of Δx is less than the absolute value of Δy. Conversely, the observation is "close" to the east-west boundary if the absolute value of Δx is greater than the absolute value of Δy.

This example applies specifically to the orientations given in Figure 4. For general application, the starting direction and Δx and Δy are tested to determine which orientations of end points will result in route violations.

Type

If the vehicle types (eg articulated truck, car) recorded at the start and end points of a candidate match differ, then the candidate match is regarded as failing the type criterion. As with the other criteria, a user-specified penalty factor is applied to the weighting of the candidate match.

Mistaking the vehicle type, however, is a common observer error in a number plate survey. This was confirmed using the matching programs discussed in the next section. The penalty factor for mismatched types should therefore not be severe. In the case study described later, vehicle types were often inconsistently recorded. Because of this, a penalty factor of 1.0 was used, effectively ignoring the type information.

On smaller scale surveys with trained observers and relatively slow moving vehicles, vehicle types may be more accurately recorded. In these cases it would be practical to lower the penalty factor, so that vehicle type is a more significant criterion.

An example

A series of potential matches is given in Figure 5.

The relevant threshold and penalty factors for the match are:

- Traversal time t_t 30 minutes
- Low speed threshold 15 km/h
- Local density threshold factor 1.5
- Weighting threshold w_t 0.6
- Maximum weighting w_{max} 1.0
- Low speed penalty 0.7
- Local density penalty 0.75
- Route (turnabout) penalty 0.6
- Type penalty 0.95

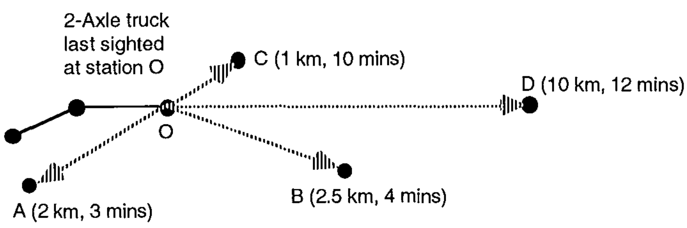

Figure 5 An example matching situation

The trip information for each potential match is listed in Table 1.

Table 1 Trip parameters for match example

Match	Vehicle type	Local density	Speed	Route violation	Local density violation	Low speed violation	Type violation
A	Bus	2 km	40 km/h	Yes	No	No	Yes
B	2 Axle	3 km	38 km/h	No	No	No	No
C	2 Axle	2 km	6 km/h	No	No	Yes	No
D	2 Axle	3 km	50 km/h	No	Yes	No	No

The weightings for each match are calculated in Table 2.

Table 2 Initial and final weightings of matches

Match	Initial weighting	Application of penalty factors
A	$1 - \frac{3}{30}(1 - 0.6) = 0.9600$	0.9600 x 0.6 x 0.95 = 0.5472
B	$1 - \frac{4}{30}(1 - 0.6) = 0.9467$	0.9467 (no penalty)
C	$1 - \frac{10}{30}(1 - 0.6) = 0.8667$	0.8667 x 0.7 = 0.6067
D	$1 - \frac{12}{30}(1 - 0.6) = 0.8400$	0.8400 x 0.75 = 0.6300

The chosen match is therefore B, since it is above the weighting threshold (0.6) and has the highest weighting.

If the general behaviour of vehicles around station O was observed in a real OD survey, it is plausible that some vehicles would travel from O to A, since A is relatively close to O. If the route penalty factor was not too severe, most of these vehicles should be correctly matched between O and A. However, some may be matched elsewhere, particularly if the route penalty is significant. This scenario demonstrates a slight limitation in the route criterion for observations which appear behind the starting point of a match. This limitation may be alleviated by using the iterative route-checking technique described earlier in the discussion of the route criterion.

Residual matching

After matching is completed, there will generally be a relatively large number of unmatched observations remaining (residuals). The residual observations arise from three sources:

1. Isolated sightings which are correctly identified as not being a part of any trip.
2. Number plate sightings which were recorded incorrectly by observers (for example A758 being confused with A75B).
3. Sightings which should have been matched into a trip, but weren't.

The algorithm treats every residual as a potential observer error (case 2). During matching each residual is stored in a disk file for later retrieval. After all residuals have been identified in this way, the entire matching procedure is performed again, but with an important difference. When a series of observations for a given number plate is read in, the file of residuals is consulted for number plates similar to the given number plate.

Similar number plates are those that:

- are graphically similar (have a similar appearance, for example I700 and 1700);
- are phonetically similar (sound similar when spoken aloud, for example M250 and N250);
- have adjacent characters transposed (for example R324 and R342); or
- have one character different (for example T992 and T292)

Any residuals considered to be similar are added to the list of candidates for matching. For example, if all records of the partial number plate A166 were being examined, then residual sightings of AI66 (graphically similar) and 8166 (phonetically similar) could be added to the list of observations.

After the similar residuals have been added to the list of candidates, they are considered for each match along with the conventional observations. The user can control the likelihood of residual matches being made by specifying an additional penalty factor to be applied to each residual observation. This penalty factor reduces the weighting of the match in conjunction with the speed, local density and route penalty factors. If a residual is successfully matched into a trip, it is removed from the pool of available residuals so that it is not matched more than once.

IMPLEMENTATION OF THE ALGORITHM

General

Three needs were identified in the implementation of the algorithm.

1. The user must be able to change the matching parameters (threshold and penalty factors, traversal time etc.) and be able to see the effects of those changes. Such experimentation would enable the parameters to be tailored to suit the OD survey being analysed.
2. The program must perform the matching in a robust manner. Anomalies such as negative travel times should not cause the program to fail. The user should also have control over the extent of residual matching.
3. The results of the analysis should be presented in a meaningful way. The user should be able to query the database of matched routes and obtain a breakdown of the routes and the number of vehicles travelling along each.

A suite of three computer programs was written by the author to address each of the three needs and to demonstrate the features of the algorithm. The three programs, *OD-Preview*, *OD-Match* and *OD-Query* are described below.

OD-Preview

OD-Preview allows the user to change the matching parameters and interactively see the matching take place on a map of the study area. Each proposed match generated by the algorithm is presented to the user, with the calculated weightings and criteria. The user may accept the suggested match or manually select a different observation to view the effect on the matching process. The matching parameters may be changed at any point (see Figure 7). Once the user is satisfied with the matches being produced by the set of chosen matching parameters, the parameters can be saved to disk in readiness for the actual analysis by *OD-Match*.

OD-Preview also lets the user examine the raw data from the survey without the tedium of deciphering columns of times, directions and station numbers. The program uses a fast binary search to find any number plate that the user specifies. Observations for the specified number plate are listed chronologically on the side of the screen. By selecting an observation, the user can see it plotted on the map. An illustration of the interactive matching feature of *OD-Preview* is given in Figure 6.

OD-Match

OD-Match allows the residual matching options to be set and performs the actual matching of the data. A dialogue box is used to select which similar letters and numerals will be used in identifying residual number plates to match. The user may also set the penalty factors for residual matching (see Figure 8).

If the user wishes to focus on a small part of the study area, *OD-Match* lets the user define a sub-area of stations. This sub-area may then be analysed as a separate entity—all observations outside the sub-area are discarded.

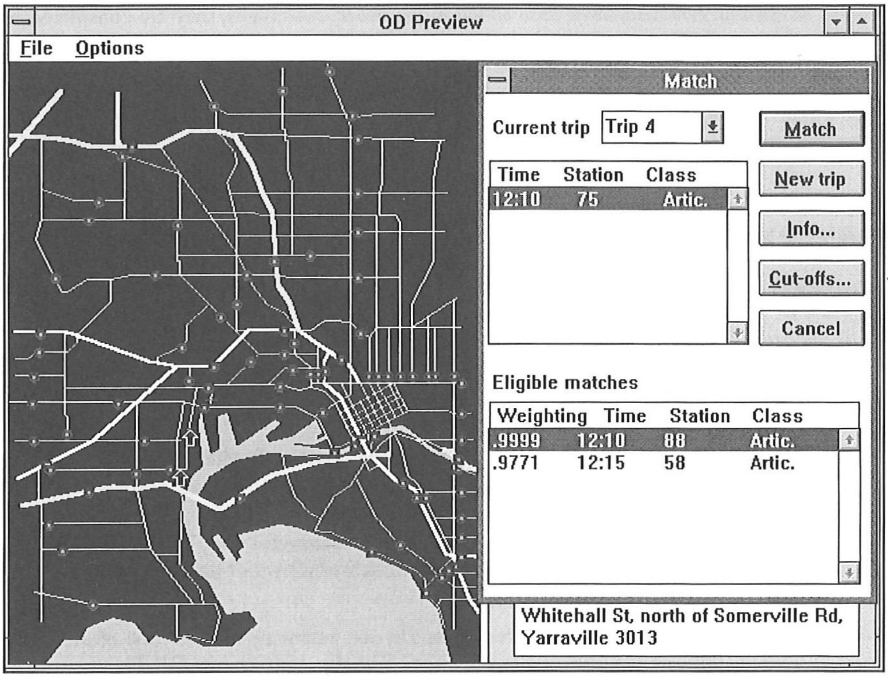

Figure 6 **Interactive matching in *OD-Preview***

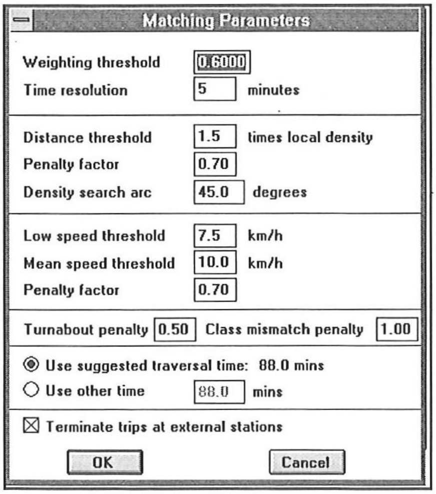

Figure 7 **Dialogue box allowing the user to change the matching parameters**

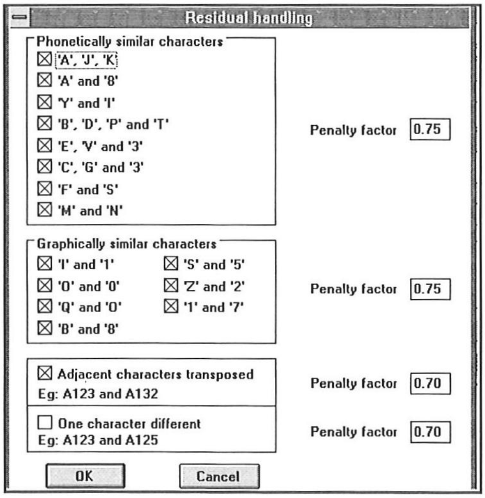

Figure 8 **Residual matching dialogue box**

OD-Match uses the algorithm shown in Figure 2 to match the data. The first matching pass produces a file of residuals. The second pass attempts to match residuals into trips and writes the final matched trips to a file for use by *OD-Query*.

OD-Query

OD-Query displays the results of the analysis in three ways: as an OD matrix displaying the numbers of vehicles travelling from each origin to each destination station; as routes plotted on a map of the study area; and as desire lines.

Routes may be selected by interpolation. The user specifies the starting and terminating points of a route as well as any desired internal stations. All routes which pass from the starting point to the termination point and also pass through the specified internal stations will be retrieved from the database. The program can therefore answer queries such as "How many vehicles travel from station 5 to station 12, and what are all the routes being used in travelling between these stations?".

CASE STUDY: THE NORTHERN AND WESTERN SUBURBS TRUCK STUDY

In 1992 the consulting firms Gutteridge Haskins & Davey Pty Ltd (GHD) and Australasian Traffic Surveys conducted a quantitative study of truck movements in the central metropolitan area of Melbourne, Australia. The main objective of the Northern and Western Suburbs Truck Study was to establish the more heavily trafficked truck routes in Melbourne with special emphasis on the Footscray area.

A large-scale OD number plate survey was the chosen study method. Truck number plates and vehicle classifications were collected over a 24 hour period from 88 observation stations within a 10 kilometre radius of Melbourne's GPO. The raw data obtained from the survey were matched using a conventional matching program.

The *OD-Match* suite of programs has since been used to compare the performance of the improved algorithm with the conventional algorithm. A map of the study area used by the *OD-Match* program suite appears in Figure 6.

The OD matrices produced by each program are given in Figures 9 and 10 as three-dimensional plots. The horizontal axes contain the numerical identifiers of each origin and destination station. The heights of the peaks (vertical axis) correspond to the numbers of vehicles travelling from the origin stations to the destination stations given on the horizontal axes.

The most striking difference between the two matrices is the cluster of peaks along the diagonal of the conventional matrix (Figure 9). This cluster does not appear in the matrix produced by *OD-Match* (Figure 10). The diagonal elements of an OD matrix are those trips which originate and terminate at the same station, that is, vehicles that travel in a loop back to their starting point.

Such looping trips are likely to be erroneous in a truck survey. If a truck is observed entering and leaving the study area at the same point, it has probably stopped somewhere in the area to make a pick-up or delivery before returning. If a stop does actually occur, the survey analysis should desirably record the truck as having made at least two trips—one *to* the stopping point and one *from* the stopping point. The absence of significant peaks along the matrix diagonal in Figure 10 indicates that the improved algorithm has correctly detected stops in looping vehicles' trips.

The two matrices are similar in most other respects. The magnitudes of the high peaks (heavily-used routes) agree closely. It is difficult to determine the absolute accuracy of the improved algorithm without knowledge of the exact vehicle movements that happened during the survey. Relative to the conventional algorithm, however, the improved algorithm appears to have enhanced the quality and accuracy of the results, by eliminating the looping trips which appear not to enter and leave the study area at the same place, without having made an intermediate stop.

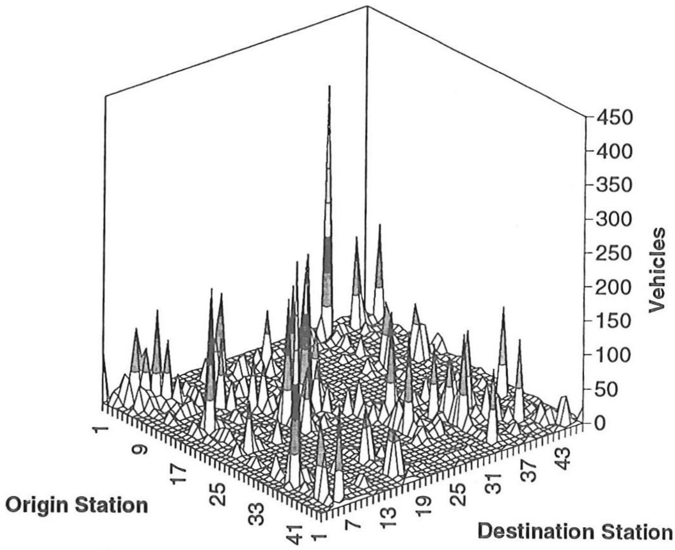

Figure 9 **Conventional algorithm external stations OD matrix**

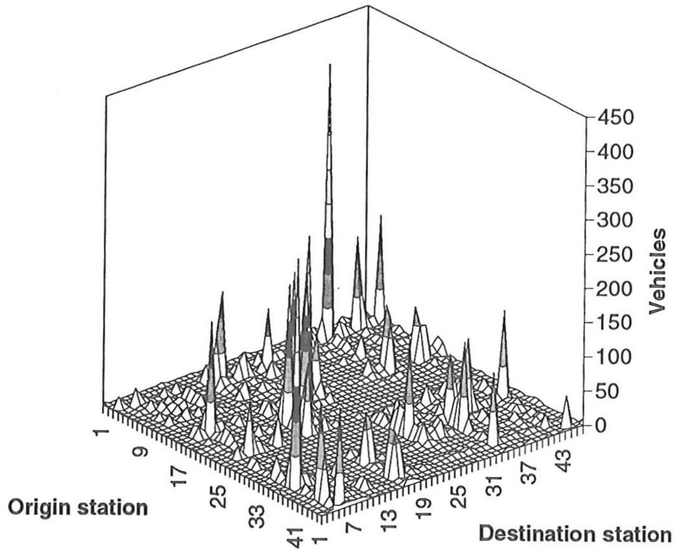

Figure 10 **OD-Match external stations OD matrix**

CONCLUSION

The improved algorithm proposed in this paper has been shown to produce more accurate results than a conventional algorithm when applied to a large-scale OD number plate survey. This improvement was gained by using spatial, temporal and logical criteria to make the best possible choices for each match, consequently reducing the incidence of spurious matching.

It should be emphasised, however, that many of the benefits of an improved algorithm will be overshadowed if data collection techniques are poor. Missing data, in particular, will limit the accuracy of any algorithm.

The algorithm could be further improved by iterating the analysis as described under the route criterion in the Matching criteria section . During the first matching pass a database of routes could be built. The probabilities of vehicles moving between each pair of stations could then be estimated. In the second matching pass, these probabilities could be used to calculate more accurate values of the route penalty factors. Residual matching could also occur during the second pass.

Another useful extension to the *OD-Match* suite of programs would be to integrate the matching algorithm with a geographic information system (GIS). A GIS would allow greater accuracy in on-road distance measurement and could provide auxiliary information such as the shortest paths between stations. A GIS could also provide more sophisticated mapping facilities to allow, for example, vehicle routes to be overlaid on maps of land-use.

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