SCIREA Journal of Agriculture

http://www.scirea.org/journal/Agriculture

October 10, 2016

Volume 1, Issue1, October 2016

A new turning movement algorithm for special road junctions

Sabah Said Razouki[1], Ph.D., Dipl.-Ing., CEng., AM.ASCE
Saad Yousif[2], Ph.D., M.Sc.

[1]Former Professor of Civil Engineering
College of Engineering, Al-Nahrain University, Baghdad, Iraq
nspsf2004@yahoo.com (Corresponding author)

[2]Senior Lecturer, University of Salford, Manchester M5 4WT, UK

s.yousif@salford.ac.uk

Abstract:

Presented in this paper is a new algorithm based on matrix algebra for determining turning movements at special road junctions in which certain movements within the junction are prohibited. This is achieved by developing mathematical models based on continuity of flow and the fact that the number of linearly independent equations is equal to the number of unknown traffic streams. The models have practical use in reducing the number of detectors or counters needed in collecting the turning movements from each arm/link of a junction and have the advantage of reducing the time required for the analysis of traffic survey data. These models were validated against data obtained from different sites in different countries and excellent agreement was found between the calculated and actual turning movements. The paper reveals that the solution vector for each case is unique and relatively insensitive to light U-turns.

Key words: mathematical model, road junctions, turning movements.

Notation

E_i : traffic entering the road junction from road i

L_i : traffic leaving the road junction from road i

n : number of roads connected by the junction

S_{ij} : traffic flow counts at the internal section (between links i and j)

T_{ij}: traffic flow counts from road i to road (arm or leg) number j

vph : vehicle per hour

W_{ij} : traffic flow counts at an internal circulating section between arms i and j in a rotary (roundabout)

Introduction

It is well-known that there is an increasing demand to collect quality traffic data for road junctions for a variety of uses such as traffic control and geometric design. Turning movement data for a road junction can be collected by automatic counters, videoing techniques or manual methods (which are very common in most developing countries).However, there may be occasions where the number of detectors (or traffic counters) were reduced due to site limitations caused by faulty or limited number of counters used, inaccessible sections for obtaining video images for later analysis (e.g. presence of sharp bends, buildings or large trees obscuring vision).

Currin (2013) presented thoroughly the process of manual turning movement count at road intersections. Apparently, he restricted his application to a road-crossing with twelve possible turning movements (no U-turns). In his practical example, he showed that the total inflow to the intersection is equal to the total outflow from it. It appears also that Currin (2013) did not pay any attention to the possible use of mathematical models to simplify the process of gathering and analysing the data. For this reason he did not carry out any flow counts at any internal section in the intersection.

Several researchers attempted to estimate turning movements at road junctions and a number of methods were developed over the years making use of traffic flows entering and leaving a junction (for example, see Jeffreys and Norman (1979), Razouki and Jadaan (1997) and Razouki (2000)). Eisenman and List (2005) used detailed information on individual vehicle's trajectories through the rotary and proposed estimates of turning movements. The accuracy of turning flow estimates at road junctions from traffic counts was also examined by Bell (1984) who accepted a relative difference of about 22.5% for traffic flows in the region of about 1575 vph and an absolute difference of 74 vph for traffic flows of 454 vph. Jadaan (1989) studied the accuracy of turning flows and accepted a relative difference between actual and estimated flow of 13.1% for traffic flows of 168 vph.

Findley et al. (2011) compared various data collected using typical manual methods with data taken from moving vehicles with the traffic. Lower accuracy was found using the mobile-collected data, but in some cases this was found to be comparable to actual true data. Based on an empirical study by Zheng and McDonald (2012) in which video recordings were used, the errors in 5-minuute counts were reported to be less than 1% and errors in vehicle classification were between 4 and 5%. The accuracy of estimation of turning flow counts data gathered manually at four intersections has been tested by Adebisi (1987). The findings suggested that the higher the number of legs in an intersection, the lower the accuracy of estimation and that the models used for providing the magnitude of error in estimation (i.e. the Fratar, Furness and Kruithof models) all provided similar results. However, the estimation of turning movements relied heavily on the initial model inputs.

The manual method is the most expensive especially when the traffic flow is high and the junction is large. In addition, the analysis of data to get the turning movements matrix is time consuming and therefore costly. The use of automatic detectors is much economical if they can yield the traffic matrix with the help of mathematical models.

The task of collecting good quality data for road junctions is rather difficult due to the resources needed in conducting such a traffic survey. The traffic engineer aims at achieving a very economic and optimum solution for determining turning movements at road intersections. This requires the reduction or elimination, if possible, of manual workers (observers)/data collectors to cut the cost of such traffic surveys. Thus, this requires in turn the development of mathematical models having the number of traffic streams equal to the available linearly independent equations for that junction. The aim of the present paper will be achieved when dealing with “traffically determinate”(a term which is explained below) road junctions having a matrix equation that has a unique solution through matrix inversion. Such a solution requires just the substitution of,for example, all the inflow counts and all outflows except one (any one) and one count at an internal section of the junction as described below.

1. “Traffically Determinate” Junctions

Similar to “statically determinate” and “statically indeterminate” structures in Civil and Structural Engineering , road junctions can be classified into “traffically determinate” and “traffically indeterminate” road junctions (Razouki, 1997,Razouki and Jaddan, 1997,Razouki, 2000), where:

- a “traffically determinate” road junction: is one that provides a number of linearly independent system of simultaneous algebraic equations equal to the number of traffic streams in that junction, and
- a “traffically indeterminate” road junction: is one that provides a number of linearly independent simultaneous algebraic equations which is less than the number of traffic streams in that intersection.

However, the present paper is restricted to “traffically determinate” T-junctions, three-arm rotaries and road crossings only.

2. Mathematical Models’ Assumptions

As discussed above, the mathematical models to be developed here depend only on flow counts at certain sections of the junction. These counts should be obtained easily by unskilled laborers, automatic counters or from video cameras. To arrive at a logical and simple model for use in accurately estimating turning movements at each type and condition of a “traffically determinate” road junction, the following assumptions are made:

i. Traffic flow through the road junction is continuous. Thus, parking within the intersection is not allowed.

Accordingly, the following equation of continuity of flow applies:

$$\sum_1^n E_I = \sum_1^n L_i \qquad (1)$$

Where,

E_i =traffic entering the road junction from road i
L_i= traffic leaving the road junction from road i
n = number of roads connected by the junction.

ii. No U-turns. That means there is no traffic flow from and to the same road (or arm or leg of the junction).

Accordingly:

$$T_{ii} = 0 \qquad \text{for all i-values} \qquad (2)$$

Where,

T_{ii} = traffic flow from and to road (arm or leg) number i.

iii. Traffic is homogeneous. That means the traffic composition is the same for all roads of the junction.

For the case of mixed traffic, each traffic category can be treated separately.

3. Formulation of Mathematical Models

Based on the assumptions made above, the mathematical models for “traffically determinate” road junctions can be formulated bearing in mind that each section count yields one equation. To arrive at a linearly independent system of algebraic equations for a junction, one section count either at an entrance to or exit from the junction, should be omitted and replaced by a section count inside the intersection.

Note that for the case of inconsistent in- and out-flows, which is common when using automatic traffic counters, the Van Zuylen (1979) correction method can be applied to increase the accuracy of results of the mathematical models. Similarly, automatic counts should be corrected for undercounting and proper correction factors for three-

arm rotaries are presented and applied by Razouki and Jadaan (1997).
For this purpose, the mathematical model for each of the following four “traffically determinate” road junctions is to be developed.

4.1 Mathematical Model for a Road T-Junction

For the T-junction shown in Figure 1, cross-section counts at all entrances and exits of the three roads of the junction should be carried although one of these counts could be cancelled but it is useful to use it for checking the validity of Equation 1.

These counts yield five equations. The necessary additional internal section, for example, $\mathbf{S_{23}}$ shown in Figure 1, will provide the sixth equation of the system of linearly independent algebraic equations. In matrix form, this system of equations, after omitting L_3,becomes:

$$\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T12 \\ T13 \\ T21 \\ T23 \\ T31 \\ T32 \end{bmatrix} = \begin{bmatrix} E1 \\ E2 \\ E3 \\ L1 \\ L2 \\ S23 \end{bmatrix} \qquad (3a)$$

or,

$$A \cdot B = C \qquad (3b)$$

where,

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 \end{bmatrix} = \text{coefficient matrix} \qquad (3c)$$

$B=[T_{12} T_{13}\ T_{21} T_{23} T_{31}\ T_{32}]^T$=column vector of unknown traffic streams

(3d)

$C= [E_1\ E_2\ E_3\ L_1\ L_2\ S_{23}]^T$ = column vector of known traffic counts (3e)

The coefficient matrix A is a non-singular matrix having a non-zero determinant of 2 and hence the system of equations is linearly independent (Wylie and Barrett, 1985; Kreyszig 2006) and the matrix inverse exists. It should be noted that this model (Equation 3a) will change only if instead of L_3, any other external cross-section count is to be omitted.

4.2 Mathematical Model for a Three-Arm Rotary

For a three-arm roundabout (or three-leg rotary or traffic circle), flow counts should be carried out at all entrances and exits of the rotary similar to the case of the T-junction. However, the internal section in this case is a cross-section in any circulating section, for example, W_{12} as shown in Figure 2 (in which the numbering of the radial roads or arms is counter clockwise). Omitting L_3 in formulating the model, the following mathematical model in matrix form is obtained:

$$\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} T12 \\ T13 \\ T21 \\ T23 \\ T31 \\ T32 \end{bmatrix} = \begin{bmatrix} E1 \\ E2 \\ E3 \\ L1 \\ L2 \\ W12 \end{bmatrix} \qquad (4)$$

Here again, the coefficient matrix is non-singular having a non-zero determinant of 1.

4.3 Mathematical Model for a Road Crossing with Directional Islands for Right Turns

There are sometimes road crossings with some channelization through directional islands for right turning movements or pavement markings on separate lanes devoted to right turns only. However, the number of unknown traffic streams in a road crossing, under the assumptions made above, is 12.

Thus, 12 linearly independent algebraic equations are required. The available equations from counts at the entrances, exits and one internal section in the junction yield 8 equations. The remaining 4 equations required can be obtained in this case by counting separately the right turning movements. Thus, this type of crossing is “traffically determinate”.

According to Figure 3, the separate counts for right turns yield:

$$\begin{aligned} T_{12} &= E_{12} \\ T_{23} &= E_{23} \\ T_{34} &= E_{34} \\ T_{41} &= E_{41} \end{aligned} \qquad (5)$$

Thus, the number of unknown traffic streams becomes 8 and, after omitting L_4 and using the internal section S_{24} as shown in Figure 3, the corresponding system of linearly independent algebraic equations in matrix form becomes

$$\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} T13 \\ T14 \\ T21 \\ T24 \\ T31 \\ T32 \\ T42 \\ T43 \end{bmatrix} = \begin{bmatrix} E1 - T12 \\ E2 - T23 \\ E3 - T34 \\ E4 - T41 \\ L1 - T41 \\ L2 - T12 \\ L3 - T23 \\ S24 \end{bmatrix} \qquad (6)$$

The coefficient matrix of Equation 6 is non-singular as it has a non-zero determinant of **2.**

4.4 Mathematical Model for a Road Crossing with Prohibited Left Turns

There are some road crossings with signs prohibiting left turns from all corresponding four roads, especially in busy town centers. In this case, the number of unknown traffic streams is 8 and the number of available linearly independent algebraic equations from the traffic counts is also 8 indicating that this crossing is "traffically determinate". The traffic counts should cover all entrances, exits and one internal section, such as section S_{24} of the crossing shown in Figure4. The corresponding matrix equation, after omitting L_4, becomes:

$$\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T12 \\ T13 \\ T23 \\ T24 \\ T31 \\ T34 \\ T41 \\ T42 \end{bmatrix} = \begin{bmatrix} E1 \\ E2 \\ E3 \\ E4 \\ L1 \\ L2 \\ L3 \\ S24 \end{bmatrix} \qquad (7)$$

The coefficient matrix of Equation 7 has a non-zero determinant of **-2** indicating that this matrix is non-singular and hence the equations are linearly independent**.**

5. Solution Vectors

To arrive at the required traffic streams and hence the origin-destination matrix for each of the four "traffically determinate" road junctions discussed above, the solution of each of Equations 3a,4,6 and 7 is required.

To save on computing time, it is best to make use of the inverse matrix approach for solving each of the four introduced mathematical models. This is due to the fact that the matrix inverse of the coefficient matrix of each of the above mathematical models remains unchanged even when the right-hand column vector of known quantities (counts outside and inside the junction) changes. This is the great advantage of this approach compared with the Gaussian elimination approach used by Yousif and Razouki (2007). When the right-hand column vector of any of the above mathematical models changes, the Gaussian elimination should be repeated as it covers both sides of the matrix equation.

Using the matrix inverse approach, for example, on Equation 3b, the solution vector becomes:

$$B = A^{-1} C \qquad (8)$$

where,

A^{-1} = inverse of the coefficient matrix A.

5.1 Origin-Destination Matrix for T-Junctions

To arrive at the unknown traffic streams for any T-junction such as that shown in Figure 1, the inverse of matrix A given by Equation 3c is required. Using, for example, Microsoft Excel, this inverse becomes:

$$A^{-1}=\begin{bmatrix} 0.5 & 0 & -0.5 & 0.5 & 0.5 & -0.5 \\ 0.5 & 0 & 0.5 & -0.5 & -0.5 & 0.5 \\ -0.5 & 0 & -0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 & -0.5 & -0.5 & -0.5 \\ 0.5 & 0 & 0.5 & 0.5 & -0.5 & -0.5 \\ -0.5 & 0 & 0.5 & -0.5 & 0.5 & 0.5 \end{bmatrix} \quad (9a)$$

By substituting this inverse matrix into Equation 8 and taking Equation 3e into account, the following solution vector for the required six traffic streams is obtained:

$$B=\begin{bmatrix} T12 \\ T13 \\ T21 \\ T23 \\ T31 \\ T32 \end{bmatrix} = 0.5\begin{bmatrix} E1-E3+L1+L2-S23 \\ E1+E3-L1-L2+S23 \\ -E1-E3+L1+L2+S23 \\ E1+2E2+E3-L1-L2-S23 \\ E1+E3+L1-L2-S23 \\ -E1+E3-L1+L2+S23 \end{bmatrix} \quad (9b)$$

Thus, it is quite obvious from Equation 9b that the traffic engineer has just to substitute the required traffic counts to obtain the required traffic streams and accordingly the O-D matrix as it will be shown later. This is a rather direct and very economic approach for determining the turning movements at T-junctions.

5.2 Origin-Destination Matrix for Three-Arm Rotaries

For the case of a three-arm roundabout (three-leg rotary), the matrix inverse of the coefficient matrix of Equation 4 is given by:

$$A^{-1}=\begin{bmatrix} 1 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & -1 & 1 \\ -1 & 0 & -1 & 1 & 0 & 1 \\ 1 & 1 & 1 & -1 & 0 & -1 \\ 1 & 0 & 1 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (10a)$$

Thus, Equation 8 yields:

$$B=\begin{bmatrix} T12 \\ T13 \\ T21 \\ T23 \\ T31 \\ T32 \end{bmatrix} = \begin{bmatrix} E1+L2-W12 \\ -L2+W12 \\ -E1-E3+L1+W12 \\ E1+E2+E3-L1-W12 \\ E1+E3-W12 \\ -E1+W12 \end{bmatrix} \quad (10b)$$

The solution vector given by Equation 10b provides the corresponding O-D matrix as it will be shown later.

5.3 Origin-Destination Matrix for Cross Roads with Directional Islands for Right Turns

For the case of a road crossing with directional islands for right turns or with right turn only pavement marking, the matrix inverse of the coefficient matrix of Equation 6 is given by:

$$A^{-1}=\begin{bmatrix} 0.5 & 0 & 0 & -0.5 & 0.5 & 0.5 & 1 & -0.5 \\ 0.5 & 0 & 0 & 0.5 & -0.5 & -0.5 & -1 & 0.5 \\ -0.5 & 0 & -1 & -0.5 & 0.5 & 0.5 & 0 & 0.5 \\ 0.5 & 1 & 1 & 0.5 & -0.5 & -0.5 & 0 & -0.5 \\ 0.5 & 0 & 1 & 0.5 & 0.5 & -0.5 & 0 & -0.5 \\ -0.5 & 0 & 0 & -0.5 & -0.5 & 0.5 & 0 & 0.5 \\ 0.5 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0 & -0.5 \\ -0.5 & 0 & 0 & 0.5 & -0.5 & -0.5 & 0 & 0.5 \end{bmatrix} \qquad (11a)$$

According to Equation 8, the solution vector becomes:

$$B=\begin{bmatrix} T13 \\ T14 \\ T21 \\ T24 \\ T31 \\ T32 \\ T42 \\ T43 \end{bmatrix} = 0.5\begin{bmatrix} E1-2E12-E4+L1+L2+2L3-2E23-S24 \\ E1+E4-L1-L2-2L3+2E23+S24 \\ -E1-2E3+2E34-E4+L1+L2+S24 \\ E1+2E2-2E23+2E3-2E34+E4-L1-L2-S24 \\ E1+2E3-2E34+E4-2E41+L1-L2-S24 \\ -E1-E4+2E41-L1+L2+S24 \\ E1-E12+E4-2E41+L1+L2-E12-S24 \\ -E1+2E12+E4-L1-L2+S24 \end{bmatrix}$$

(11b)

5.4 Origin-Destination Matrix for Cross Roads with Prohibited Left Turns

For this case, the matrix inverse of the coefficient matrix of Equation 7 is given by:

$$A^{-1}=\begin{bmatrix} 0.5 & 0 & 0 & -0.5 & 0.5 & 0.5 & 0 & -0.5 \\ 0.5 & 0 & 0 & 0.5 & -0.5 & -0.5 & 0 & 0.5 \\ -0.5 & 0 & 0 & -0.5 & 0.5 & 0.5 & 1 & -0.5 \\ 0.5 & 1 & 0 & 0.5 & -0.5 & -0.5 & -1 & 0.5 \\ -0.5 & 0 & 0 & -0.5 & 0.5 & 0.5 & 0 & 0.5 \\ 0.5 & 0 & 1 & 0.5 & -0.5 & -0.5 & 0 & -0.5 \\ 0.5 & 0 & 0 & 0.5 & 0.5 & -0.5 & 0 & -0.5 \\ -0.5 & 0 & 0 & 0.5 & -0.5 & 0.5 & 0 & 0.5 \end{bmatrix} \qquad (12a)$$

Using Equation 8,the solution vector becomes:

$$B=\begin{bmatrix} T12 \\ T13 \\ T23 \\ T24 \\ T31 \\ T34 \\ T41 \\ T42 \end{bmatrix} = 0.5\begin{bmatrix} E1-E4+L1+L2-S24 \\ E1+E4-L1-L2+S24 \\ -E1-E4+L1+L2+2L3-S24 \\ E1+2E2+E4-L1-L2-2L3+S24 \\ -E1-E4+L1+L2+S24 \\ E1+2E3+E4-L1-L2-S24 \\ E1+E4+L1-L2-S24 \\ -E1+E4-L1+L2+S24 \end{bmatrix} \qquad (12b)$$

Thus, using Equation 12b, the required Origin-Destination matrix can be constructed.

6 Validation of the Developed Models

For the validation of the developed mathematical models for the different "traffically determinate" road junctions discussed above, actual data is required.

6.1 Case of a T-Junction

Very suitable data for a traffically determinate T-junction was presented by Adebisi (1987).In fact, Adebisi (1987) presented two manual counts for Leventis T-junction in Zaria , Nigeria. Table 1 presents the first hourly count (Saturday ,March 2,1985)for this junction using the road numbering system of this work.

Thus, the substitution of all inflows and outflows except L_3 into equation 9b yields

$$B = 0.5\begin{bmatrix} 954-1289+635+694-952 \\ 954+1289-635-694+952 \\ -954-1289+635+694+952 \\ 954+2*326+1289-635-694-952 \\ 954+1289+635-694-952 \\ -954+1289-635+694+952 \end{bmatrix} = \begin{bmatrix} 21 \\ 933 \\ 19 \\ 307 \\ 616 \\ 673 \end{bmatrix} \text{vph} \qquad (13)$$

Compared with Table 1,the results are in complete agreement with the actual data indicating the validity of the developed model.

To check the sensitivity of the developed model for the case of very light U-turns ,the manual count for a T-junction in the urban area of Hilla City in Iraq carried out by Al-Shaekhli (1993) under the supervision of the senior author ,was considered suitable. The corresponding O-D matrix obtained manually is presented in Table 2 using the road numbering system of this work (see Figure 1). Note that the hourly manual count for the internal section yielded S_{23}= 383 vph.

It is quite obvious from Table 2 that there are almost no U-turns in this junction except one very light U-turn . U_{22} = 7 vph.

Thus, the substitution of all inflows and outflows, except L_3, into Equation 9b yields:

$$B = 0.5\begin{bmatrix} 344-1066+362+983-383 \\ 344+1066-362-983+383 \\ -344-1066+362+983+383 \\ 344+2(765)+1066-362-983-383 \\ 344+1066+362-983-383 \\ -344+1066-362+983+383 \end{bmatrix} = \begin{bmatrix} 120 \\ 224 \\ 159 \\ 606 \\ 203 \\ 863 \end{bmatrix} \text{vph} \qquad (14)$$

The results suggest that there is an excellent agreement between the actual data and the data obtained from the mathematical model. It is quite obvious that some of the traffic streams are unaffected at all. However, the absolute value of the maximum difference between the actual and estimated (from mathematical model) flow counts of the traffic streams is just 7 vph which represents the U-turn T_{22} = 7 vph which is overlooked by the mathematical model. This means that the mathematical model overestimated, for example, the traffic stream T_{32} by (863-856)/856=0.0082=0.82% which is completely insignificant.

6.2 Case of a Three-Arm Rotary

Razouki and Jadaan (1997) presented the manual count for a three-arm rotary from Babylon. The corresponding O-D matrix obtained manually is presented in Table 3. Note that the numbering of radial roads made by Razouki and Jadaan (1997) was clockwise. This required the swapping of the road numbers 2 and 3 by 3 and 2, respectively in order to conform to the numbering system of this work as used in Table 3.Note that the hourly manual count for the circulating section (weaving section) S_{12} was $S_{12} = 971$ vph.

It is quite obvious from Table 3 that there are U-turns in this rotary. Two of the U-turns are relatively significant making the rotary to be "traffically indeterminate". Thus, the above developed mathematical model is not valid for such a case. However, the application of the developed model on this case will give an idea about the sensitivity of the model to U-turns.

The substitution of the inflows and outflows from Table 3 together with $S_{12} = 971$ vph into Equation 10b yields the following solution vector:

$$B=\begin{bmatrix} 813+859-971 \\ -859+971 \\ -813-211+778+971 \\ 813+839+211-778-971 \\ 813+211-971 \\ -813+971 \end{bmatrix}=\begin{bmatrix} 701 \\ 112 \\ 725 \\ 114 \\ 53 \\ 158 \end{bmatrix} \text{vph} \qquad (14)$$

Table 3 shows a comparison between the actual observed traffic streams and the results of the mathematical model of this work. It is quite obvious that although the mathematical model cannot estimate the U-turns, the estimate of the remaining major traffic streams is adequate. It should be noted that the results from the model have been checked with the assumption that no U-turns are present in the actual data and for such assumption; the proposed model produced perfect results.

6.3 Case of a Crossing with Directional Islands for Right Turns

A manual classified traffic count at a road crossing in Baghdad was presented by Razouki and Sayigh (2002). The results of this count only include passenger cars, vans, pickups and mini buses (i.e. passenger car category) are listed in Table 4. The corresponding traffic count at the internal section between road No. 2 and road No. 4 was $S_{24} = 798$ vph.

Thus, the substitution of all inflows and outflows, except L_4, into Equation 11b yields:

$$
B=\begin{bmatrix} T13\\ T14\\ T21\\ T24\\ T31\\ T32\\ T42\\ T43 \end{bmatrix} = 0.5\begin{bmatrix} 378-2(92)-450+318+372+2(482)-2(106)-798\\ 378+450-318-372-2(482)+2(106)+798\\ -378-2(385)+2(130)-450+318+372+798\\ 378+2(321)-2(106)+2(385)-2(130)+450-318-372\\ 378+2(385)-2(130)+450-2(110)+318-372-798\\ -378-450+2(110)-318+372+798\\ 378-92+450-2(110)+318+372-92-798\\ -378+2(92)+450-318-372+798 \end{bmatrix}
$$

$$
=\begin{bmatrix} 194\\ 92\\ 75\\ 140\\ 133\\ 122\\ 158\\ 182 \end{bmatrix}\text{vph} \qquad (15)
$$

The comparison of the above results obtained from the mathematical model with the corresponding field data presented in Table 4 shows perfect agreement.

6.4 Case of a Crossing with Prohibited Left Turns

Road crossings with prohibited left turning movements are popular in the United States of America. Such road crossings have road signs indicating that left turns are prohibited.

In Iraq, major road crossings with prohibited left turning movements are rather uncommon. However, in residential areas ,there are many road crossings with light left turning movements. Such a road crossing was selected in a residential area in Baghdad. According to Figure 4, in this selected road crossing each of the streets 1-3 and 2-4 consists of a two-lane two way road having a pavement width of 7.00 m. At the right end of the link #2,there is an elementary school. A manual count for turning movements at this intersection was carried at morning peak between 7 to 8 am on Monday December o5,2015. Three observers were required. One observer was sufficient for each street and one observer was responsible for the volume count S_{24} at the internal section shown in Figure 4. Table 5 presents the results of the traffic survey on this intersection.

It is quite obvious from Table 5 that there are no U-turns, but there are a few light left turning movements indicating that the assumption of no “left turns” is not completely satisfied. Thus, the substitution of all inflows and outflows, except L_4, as well as the count at the internal section S_{24},into Equation 12b yields:

$$B=\begin{bmatrix}T12\\T13\\T23\\T24\\T31\\T34\\T41\\T42\end{bmatrix}=0.5\begin{bmatrix}8-44+12+43-17\\8+44-12-43+17\\-8-44+12+43+2*8-17\\8+2*49+44-12-43-2*8+17\\-8-44+12+43+17\\8+2*13+44-12-43-17\\8+44+12-43-17\\-8+44-12+43+17\end{bmatrix}=\begin{bmatrix}1\\7\\1\\48\\10\\3\\2\\42\end{bmatrix}\text{vph} \qquad (16)$$

The results obtained above from the mathematical model, are shown between brackets in Table 5. The maximum absolute difference between actual and calculated values from the model does not exceed 3 vph for the major traffic streams indicating that the mathematical model can be considered adequate even in cases of light left turning movements. It should be noted that the results from the model have been checked with the assumption that no "left turns" are present in the actual data and for such assumption; the proposed model produced perfect results.

7.Conclusions and Recommendations

The main conclusions of this work can be summarized as follows:

(1) The developed models provide unique and exact solutions for the traffic streams corresponding to the input data of inflows, outflows and traffic volume at an internal section within each junction.

(2) The developed models are applicable for homogeneous traffic. For the case of classified traffic count, the models can be applied for each traffic category separately.

(3) The use of the proposed mathematical models can save time and cut on labour costs as well as savings due to time required for the analysis in calculating the required turning movements.

(4) The is good agreement between the turning movements obtained from the models and the corresponding actual field data for different junctions in different countries.

(5) The models developed are relatively insensitive to light U-turns in the road junctions.

- Recommendations for future work include:
  - The accuracy of the model when U-turns are present requires further testing.
  - The idea of this model could be extended further to estimate missing data from O-D matrices representing several junctions (i.e. looking at a network with several links and junctions).
  - For "traffically indeterminate" junctions (i.e. rotaries with 5 arms, for example), further work may be necessary in terms of developing new models.

References

[1] Adebisi, O. 1987.Improving manual counts of turning traffic volumes at road junctions, Journal of Transportation Engineering, 113(3): 256-267.

[2] Al-Shaekhli,N.Y.1993.Optimization of number of observers for determining traffic movements at three-arm road junctions. M.Sc. thesis, College of Engineering, University of Baghdad.

[3] Bell, M.G.H. 1984. The estimation of junction turning volumes from traffic counts: the role of prior information, Traffic Engineering and Control, May, 25(5): 279-283.

[4] Currin, T.R. 2013. Introduction to traffic engineering, a manual for data collection and analysis, 2nd Edition, Cengage Learning, UK.

[5] Eisenman, S.M. and List, G. 2005.A technique for data collection and estimation of turning movements at roundabouts, Proceedings of the 84th Annual Conference of the Transportation Research Board, 2005, Washington D.C.

[6] Findley, D.J., Cunningham, C.M. and Hummer, J.E. 2011. Comparison of mobile and manual data collection for roadway components, Transportation Research Part C, 19: 521-540.

[7] Jadaan, K. 1989. Accuracy of turning flow estimates at road junctions, Journal of Transportation Engineering, ASCE, July, 115(4): 438-449.

[8] Jefferys, M. and Norman, M. 1977.On finding realistic turning flows at road junctions, Traffic Engineering and Control, January, 18(1):19-25.

[9] Kreyszig, E.2006.Advanced engineering mathematics. Ninth edition, JohnWiley &Sons, Singapore.

[10] Razouki, S.S. 1997. Modeling turning movements at traffically determinate four-arm road junction, Journal of Engineering and Development,Baghdad, Iraq,1(1): 62-71.

[11] Razouki, S.S. 2000.A mathematical model for determining the origin-destination matrix for five-arm rotaries.Journal of Engineering and Development,Baghdad, 4(3): 86-99.

[12] Razouki, S.S. and Jadaan, K.S. 1997.Estimation of turning movements at three-arm rotaries.Dirasat, An International refereed research Journal, Natural and Engineering Sciences, 24(2): 305-312.

[13] Razouki, S.S. and Sayigh, R.A.2002. No observer approach for determining turning movements at traffically determinate road crossings. Al-Muhandis 149(1):3-15.

[14] Van Zuylen HJ 1979. The estimation of turning flows on a junction. Traffic Engineering and Control, 20(11): 539-541.

[15] Wylie,C.R.and Barrett, L.C. 1985.Advanced engineering mathematics. Fifth edition, McGraw-Hill Book Company, London.

[16] Yousif, S.Y. and Razouki, S.S.2007. Validation of a mathematical model to estimate turning movements at roundabouts using field data. UTSG, Leeds, UK.

[17] Zheng, P. and McDonald, M. 2012.An investigation on the manual traffic count accuracy. 8th International Conference on Traffic and Transportation Studies, Procedia – Social and Behavioral Sciences, 43: 226-231.