Transportation Research Part C 47 (2014) 128–138

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Real-time estimation of turning movement counts at signalized intersections using signal phase information

Amir H. Ghods *, Liping Fu

Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario, Canada

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 5 February 2014
Accepted 30 June 2014
Available online 31 July 2014

Keywords:
Signalized intersection
Turning movement count
Signal phase
Least-square estimation

ABSTRACT

A variety of sensor technologies, such as loop detectors, traffic cameras, and radar have been developed for real-time traffic monitoring at intersections most of which are limited to providing link traffic information with few being capable of detecting turning movements. Accurate real-time information on turning movement counts at signalized intersections is a critical requirement for applications such as adaptive traffic signal control. Several attempts have been made in the past to develop algorithms for inferring turning movements at intersections from entry and exit counts; however, the estimation quality of these algorithms varies considerably. This paper introduces a method to improve accuracy and robustness of turning movement estimation at signalized intersections. The new algorithm makes use of signal phase status to minimize the underlying estimation ambiguity. A case study was conducted based on turning movement data obtained from a four-leg signalized intersection to evaluate the performance of the proposed method and compare it with two other existing well-known estimation methods. The results show that the algorithm is accurate, robust and fairly straightforward for real world implementation.

1. Introduction

While traffic volume in transportation networks can be easily measured by various traffic count devices, origin–destination (OD) data is more difficult to collect. OD data requires information about entrance, route, and exit of volume through the transportation facility. The matrix of OD flow at intersections, known as turning movement counts (TMC), is a critical input to the planning, design, management and operations control of urban traffic networks. For applications such as adaptive signal control, TMC plays such a crucial role and must be obtained in real-time for maximizing the effectiveness of the underlying control algorithm.

Direct measurement methods for TMC such as manual count or automatic license plate detection are found to be expensive and not feasible for on-line applications. This led to the research and development of indirect methods which estimate TMC based on easily obtainable traffic volume data. Most of these methods make use of entries and exits traffic counts at the intersection. However, the entry/exit counts are insufficient to provide the exact estimates of TMC since the underlying problem is highly undetermined with multiple solutions. To address this problem, different approaches and assumptions have been proposed and tested. Bell (1984) provides an extensive review on these assumptions and underlying methods. The methods to estimate TMC at intersections can be generally classified into two main categories of non-recursive and recursive methods. Most of these methods have taken similar approaches to minimize the prediction error between predicted and

* Corresponding author. Tel.: +1 519 888 4567x33872; fax: +1 519 888 4349.
E-mail addresses: ahghods@uwaterloo.ca (A.H. Ghods), lfu@uwaterloo.ca (L. Fu).

http://dx.doi.org/10.1016/j.trc.2014.06.010
0968-090X/

observed exit counts or to maximize the likelihood of TMC observations. A comprehensive review of maximum likelihood, Bayesian inference, and generalized least-square methods can be found in Cascetta and Nguyen (1988).

In non-recursive methods, TMC is assumed to be constant over a particular time period which can be divided into smaller time intervals for which the entry and exit volumes are measured. This method makes use of the entire data sequence to estimate the unknown TMC matrix by turning the undetermined problem to an overdetermined problem. The least-square method is a well-known solution in this category. Cremer (1983) originally used a least-square type method to estimate TMC for complex intersections. In a similar study Cremer and Keller (1987) used constraint optimization to minimize the least-square error between predicted and observed exit flow. As opposed to the least-square approach, the latter method takes into account the underlying parameters constraints in the optimization procedure. Jiao et al. (2005) used genetic algorithm to solve the same parameter optimization problem. Bell (1991a) used constrained generalized least-square (GLS) to estimate the OD matrix parameters.

In the recursive methods, the TMC parameters are estimated in a step by step process, i.e., the estimation is improved as the measure of new sample interval becomes available. Recursive least-square and Kalman filtering are well-known methods to estimate TMC in this category (e.g. in Cremer and Keller, 1987; Nihan and Davis, 1987, 1989; Bell, 1991b). Lan and Davis (1999) used two recursive algorithms of nonlinear least-square and quasi maximum likelihood to estimate TMC for an incomplete set of intersections detector counts.

Among other methods Hauer et al. (1981) used a heuristic iterative balancing approach to estimate TMC. This method, although easy to apply, was found to be sensitive to the initial solutions and the type of the intersection being considered (Schaefer, 1988). Virkler and Kumar (1998) used loop detector data to directly match output/input counts. This method appears to be sensitive to missing loop counts and randomly wrong assignment of the detections. In some studies ad-hoc solutions have been proposed to find the unknown turning movement proportion for intersections with exclusive turning lanes (e.g. in Mirchandani et al., 2001 based on signal phase information), these techniques normally require lane-by-lane detection of vehicles and would only work at channelized intersections.

A review of the existing algorithm to estimate intersection TMC reveals that the estimation quality and robustness of these algorithms varies considerably mainly due to highly undetermined nature of the underlying problem and noisy traffic counts. In this paper, we propose a new approach to find TMC for signalized intersections based on additional data available from signal phases. The idea is based on the fact that at each signal phase only particular movements are allowed. This minimizes the ambiguity among all possible solutions that may create the same entry/exit volume counts and results in more accurate and robust estimation.

2. Problem formulation

Consider the traffic movements at a signalized intersection over a particular time period. All entry and exit flows at this intersection are monitored (i.e. at stop lines and exits) and the problem is to determine the turning movement counts (TMC) over the given period based on the observed entry and exit flows.

The intersection approaches are numbered sequentially and denoted by i (entry) and j (exit), $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. For a particular time interval (k), the following variables are defined:

$q_i(k)$: total entry counts at approach i corresponding to the time interval k.
$y_j(k)$: total exit counts at approach j corresponding to the time interval k. Because of the time lag between entry and exit flow, we take into account a time shift (e.g., average travel time from an entry to an exit) in determining the exit flow.
$b_{ij}(k)$: an unknown parameter representing the TMC proportion leaving from entry i to exit j corresponding to the entry time interval k. The following conditions are applied to b_{ij} such that:

$$0 \le b_{ij}(k) \le 1 \quad \text{for all } i, j, k \tag{1}$$

$$\sum_{j=1}^{n} b_{ij}(k) = 1 \quad \text{for all } i, k$$

Based on flow conservation law, we have:

$$y_j(k) = \sum_{i=1}^{m} q_i(k) b_{ij}(k) \tag{2}$$

Assuming no U-turn for the intersection, an additional condition of the following form is given:

$$b_{ii}(k) = 0 \quad \text{for } i = 1, \ldots, \min(m, n) \tag{3}$$

The entry/exit flow, and turning movement proportion matrices for a m -entry and n-exit intersection can be introduced as follows: