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Innovative detector layout for automated traffic turning volume counting

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SUMMARY

Because of many advantages, loop detectors are the most common practice for obtaining data to control intersections. However, they have some drawbacks, including the fact that multiple detectors are usually required to monitor a location. The current practice in many cities is to install four consecutive loop detectors per lane, or two at the stop bar and one as an advanced detector. In some cities, there are also departure detectors. All these configurations have some practical problems and do not produce accurate counts especially in shared lanes. In this paper, a new placement configuration for departure detectors is proposed and named the mid-intersection detector (MID). In this configuration, departure detectors are moved back to the middle of the intersection in such a way that they can be activated by more than one movement at different times. In some cases, departure detectors lack equations for calculating turning movements, a problem solved by MIDs because each movement passes more detectors along its path (without increasing the number of loops), and therefore they can produce more accurate and reliable data for obtaining turning movement counts. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: loop detector; mid-intersection detector; turning movement volume; detector layout

1. INTRODUCTION

The problem of optimally locating sensors on a traffic network to measure flows has been the subject of growing interest in the past few years because of its relevance in transportation systems. Different locations of sensors on the network allow the collection of data, which can be useful for traffic management and control purposes. Many different models have been proposed in the literature as well as corresponding solution approaches. The proposed existing models differ according to different criteria: (i) sensor types to be located on the network (e.g. counting sensors, image sensors, and Automatic Vehicle Identification (AVI) readers); (ii) availability a-priori information; and (iii) flows of interest (e.g. OD flows, route flows, link flows, and intersection turning movements) [1].

Figure 1 depicts the different considerations for an optimal detector location. The detector location can be divided into two main categories:

1 In a network, the objective is to find an optimum location and number of detectors to obtain a defined level of counts in a network. Flows of interest are usually:

- O–D flow: One of the earliest research on estimating and observing O–D matrix is by Yang and Zhou [2]. However, a more comprehensive study that is actually a review on almost all “Optimal Traffic Counting Locations for Origin–Destination Matrix Estimation” is done by Gentili and Mirchandani [1]. More recently Lu et al. [3] used Kalman filter for this purpose.
- Screen line: Research on the problem of obtaining counts in a screen line is done by Yang et al. [4].
- Link(s) and route(s): When we locate a counting sensor on a link of the network, we measure the total flow on that link and express it as the sum of flows of the routes that use the link. Gentili

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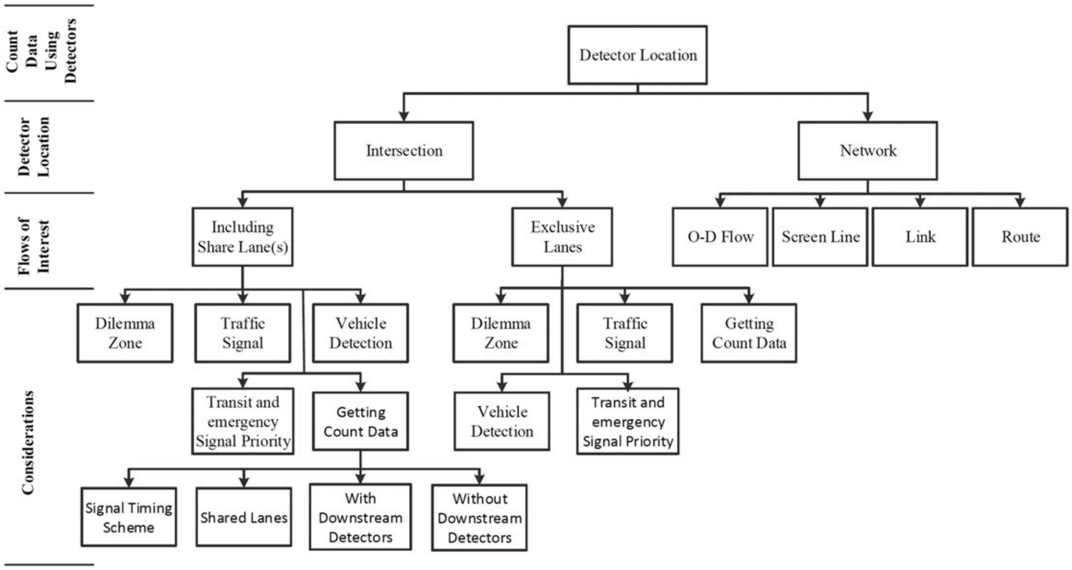

Figure 1. Detector location flows of interest and considerations.

and Mirchandani [1] have summarized models and algorithms for estimating link(s) and route(s) traffic-counting location problems. Li et al. [5] and Danczyk and Liu [6] have studied the factors which influence the sensor location at freeway corridors.

5 At an intersection, in addition to obtaining counts, some other considerations are also important. Some of these considerations are:

- Dilemma zone: Traffic Detector Handbook, Chapter 4 [7], and Traffic Control Systems Handbook, Chapter 6 [8] have described the optimum location of sensors to reduce the effect of dilemma zone on oncoming traffic.
- Optimum Vehicle detection: The position of the loop relative to the vehicles trying to be detected is extremely important. Fortunately, based on intersection geometry and the path of movements, the magnetic field sensitivity of loops can be adjusted. The ITE Traffic Engineering Council [9] has recommended the optimum location and configurations of stop bar loop detectors to obtain accurate counts.
- Traffic signal: The location of detectors can affect the optimality of signal timing. Several considerations including all-red time, yellow time, and safety of the intersection are related to detector location.
- Transit and emergency signal priority: Special configurations of inductive loops have been developed to detect axles and their relative position in a vehicle. Inductive-loop classifying sensors can preempt or alter a normal signal sequence for the movement of emergency and transit vehicles, respectively [7].
- Obtaining count data: This can be divided into two major categories where one is obtaining count data from intersections with shared lanes and the other without shared lanes. Also, intersection count data can be obtained either by intersection sensors or path flow estimators [10].

There are a number of ways to detect vehicles, ranging from hose style detection and ultra-sonic, to inductive loop. Alturi et al. [11] also proposes a new sensor system which measures both vehicle speed and counts using a transmission-based type of optical sensor rather than a reflection-based type. Among these detectors, inductive-loop detectors are very common in many city intersections. For traffic control, inductive-loop technology is the most reliable, especially compared to video image detectors. An inductive-loop detector senses the presence of a conductive metal object by inducing currents in the object, which reduces the loop inductance.

Inductive-loop detectors have the following strengths (+) and weaknesses (−) [8]:

- Flexible design to satisfy a large variety of applications.

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- Mature, well-understood technology.
- Large experience base.
- Provides basic traffic parameters (e.g. volume, presence, occupancy, speed, headway, and gap).
- Insensitive to inclement weather such as rain, fog, and snow.
- Provides best accuracy for count data compared to other commonly used techniques.
- Common standard for obtaining accurate occupancy measurements.
- High frequency excitation models provide classification data.
- Installation requires pavement cut.
- Improper installation decreases pavement life.
- Installation and maintenance require lane closure.
- Wire loops subject to stresses of traffic and temperature.
- Multiple detectors are usually required to monitor a location.
- Detection accuracy may decrease when design requires detection of a large variety of vehicle classes.

Because of practical difficulties (including loop failures) and safety issues, usually several detectors are installed in each lane, and because these detectors are connected to each other, their counts are not reliable. For this reason and also to determine turning movement counts in shared lanes, some cities use departure detectors in addition to stop bar detectors. Recently Gholami et al. [12] proposed three methods to determine turning movement counts in shared lanes without departure detectors. However, the proposed methods are not applicable for all kinds of shared lanes, and leave departure detectors are still the most reliable measure for obtaining turning movements in shared lanes. Departure detectors, also known as exit or downstream detectors, are placed in the beginning of intersection exit lanes. This configuration is not always able to produce reliable turning counts. When there are four loop detectors per lane before the stop bar, counts are extremely unreliable if loops are spliced together. As a result, it is possible several vehicles are counted as only one vehicle. In addition, departure detectors usually have two other problems. First, they cover only one movement and because a loop malfunctioning is very common in the field, the movements covered by a faulty detector remain undetected downstream. Second, with this placement configuration, the number of equations for calculating the turning movement volume is always equal or less than the number of turning movements. When the number of

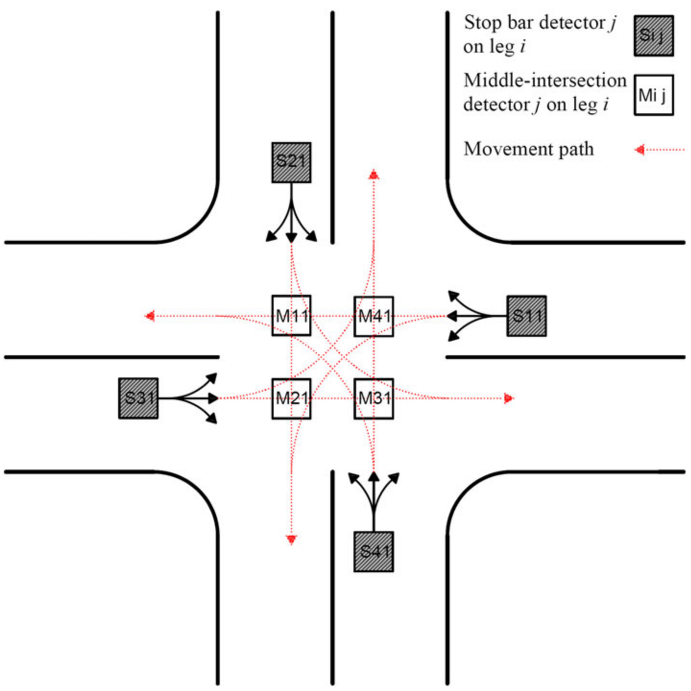

Figure 2. Mid-intersection detectors concept, Case 1.

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equations is less than the number of turning movements, there is not a straightforward method for calculating the turning movement volume.

To solve the second problem, researchers have proposed different methods including least mean square and adding traffic signal information to input data [13–21]. These methods are not straightforward because of insufficient equations for unknown movements and are not suitable for all cases, especially when there is a right turn shared lane and permitted left turn. Furthermore, they do not address the first problem.

In this paper, a new placement configuration for departure detectors has been proposed and named the mid-intersection detector (MID). MID is a better solution compared to departure detectors to solve the aforementioned two problems. In this configuration, departure detectors are moved back to the middle of the intersection in such a way that they can be activated by more than one movement at different times. MIDs solve the problem of departure detectors regarding insufficient equations for calculating turning movements, and because each movement passes more detectors along its path (without increasing the number of detectors), they can produce more accurate and reliable data for obtaining turning movement counts.

2. PROPOSED MID-INTERSECTION DETECTORS

With MIDs as the placement configuration, the number of equations is more than the number of turning movements. In this method, departure loops are moved back to the middle of the intersection (Figures 2–6), in such a way that each MID can capture more than one movement. For example, in Figure 2, detector M_{11} can capture south bound (SB) movements, west bound through (WBT), and north bound left (NBL). Therefore, in this example, while departure detectors produce only one equation, the equivalent MID can produce three equations.

Because of intersection operation, we still need stop bar detectors, but compared to other detector configurations, MIDs produce more reliable and accurate data with fewer detectors even with a non-split scheme.

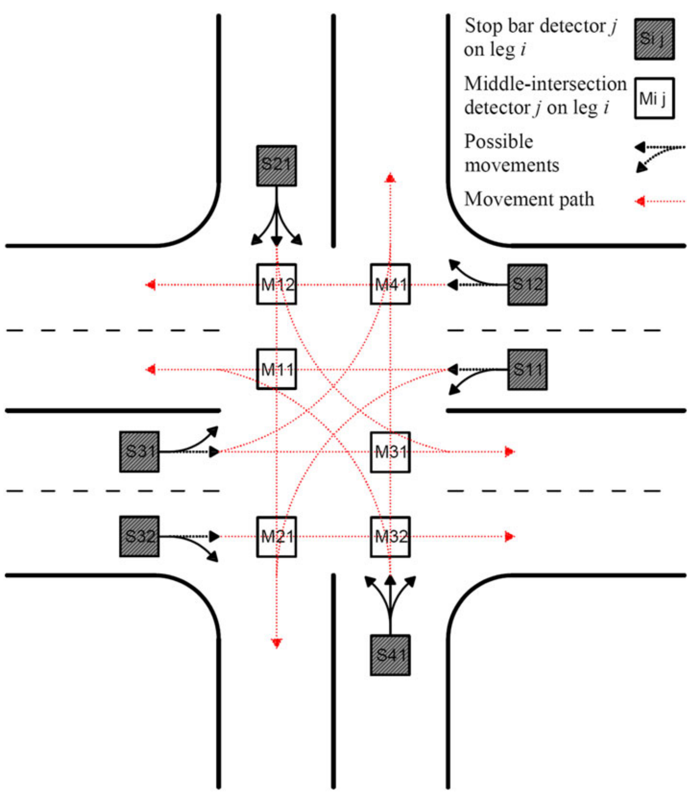

Figure 3. Mid-intersection detectors concept, Case 2.

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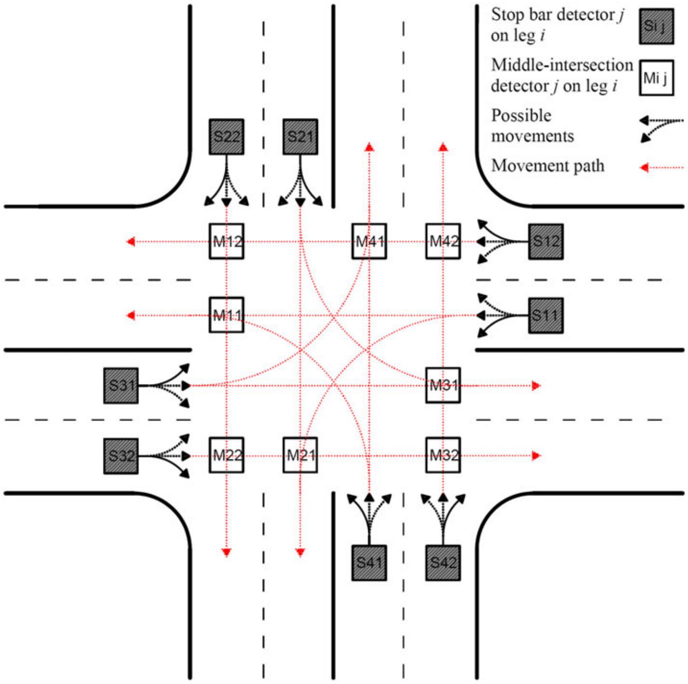

Figure 4. Mid-intersection detectors concept, Case 3.

Extracting counts from detectors is based on sequences of detector activations. For example, in Figure 2, west bound right (WBR) activates only detector S_{11} (depending on the intersection geometry, it can also activate M_{41}); west bound through (WBT) first activates detector S_{11}, then M_{41} and then M_{11}, and west bound left (WBL) first activates detector $S_{11,}$ then M_{41} and then M_{21}. These sequences of detector activations are unique, and as a result, all turning movements can be obtained.

At time t that S^t_{11} has been activated, the following function can be applied for west bound (WB):

$$S^t_{11} = \begin{cases} WBL \;\; if \;\left(M_{41}^{t+\Delta t_{S11-M41}\pm\delta}\right) \; and \; \left(M_{21}^{t+\Delta t_{S11-M21}\pm\delta}\right) \\ WBT \;\; if \;\left(M_{41}^{t+\Delta t_{S11-M41}\pm\delta}\right) \; and \; \left(M_{11}^{t+\Delta t_{S11-M11}\pm\delta}\right) \\ \qquad WBR \;\; if \;\left(M_{41}^{t+\Delta t_{S11-M41}\pm\delta}\right)^{*} \end{cases} . \qquad (1)$$

Equation 1 denotes that if there is activation at time t at stop bar, then at time $t+\Delta t_{S11-M41}\pm\delta$ detector M_{41} is activated. Finally, at time $t+\Delta t_{S11-M21}\pm\delta$ detector M_{21} is activated. Therefore, this movement should be added to WBL counts.

The variable δ indicates a time range that is possible for vehicles at a certain movement to activate a detector. For example, if the left turns are not protected, then west bound left turns before activating M_{21} should yield to east bound through (EBT), which may take several seconds (up to green time of the phase). As a result, if M_{21} is activated after $t+\Delta t_{S11-M21}\pm\delta$ seconds, it could not be WBL and may be, for example, south bound through (SBT). If the movement is protected, then δ defines the time variations that can be estimated based on speed variations. For example, if the distance between S_{11} and M_{21} is 50 ft and speed range is 20 mph to 40 mph, then vehicles reach M_{21} from S_{11} in 0.85 to 1.7 s; therefore δ is ±0.85 s, if WBL is protected. The value of δ should be determined for each movement.

For WBT, a sequence of detectors must be S_{11} then M_{41} and then M_{11}. Because of channelizing, WBR can be only S_{11}, or S_{11} then M_{41}, so the detector M_{41} is shown with an asterisk in Equation 1 that indicates that even without this activation, it is possible for a vehicle to turn right. The Δts are a function of speed and distance and can be calculated as follows:

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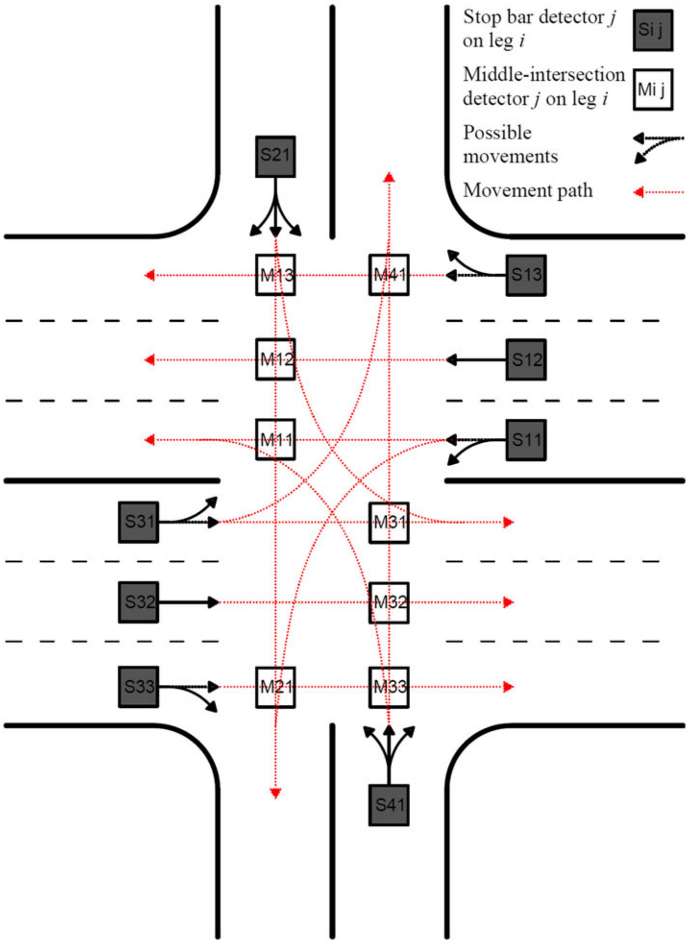

Figure 5. Mid-intersection detectors concept, Case 4.

$$\Delta t_{S_{11}-M_{41}} = \frac{x_{S_{11}-M_{41}}}{1.47\ V} \tag{2}$$

$$\Delta t_{S_{11}-M_{11}} = \frac{x_{S_{11}-M_{11}}}{1.47\ V} \tag{3}$$

$$\Delta t_{S_{11}-M_{21}} = \frac{x_{S_{11}-M_{21}}}{1.47\ V} \tag{4}$$

where:

x_{S-M} Distance between detector S to detector M (ft)
Δt_{S-M} Travel time from detector S to detector M (s)
V Average speed from detector S to detector M (mph)

Figures 3 to 6 show four other intersections. Based on the geometry of each intersection, different numbers of MIDs can be activated by a movement. For example, WBL and SBT in intersection of Figure 2 activate two MIDs, while in Figure 3, they activate one and three MIDs, respectively.

The flowchart of Figure 7 shows the process of obtaining counts from MIDs. This process is based on functions similar to Equation 1. In other words, it extracts counts from the sequences of activations. The simplest case is when all left turns are protected. However, even when movements are permitted,

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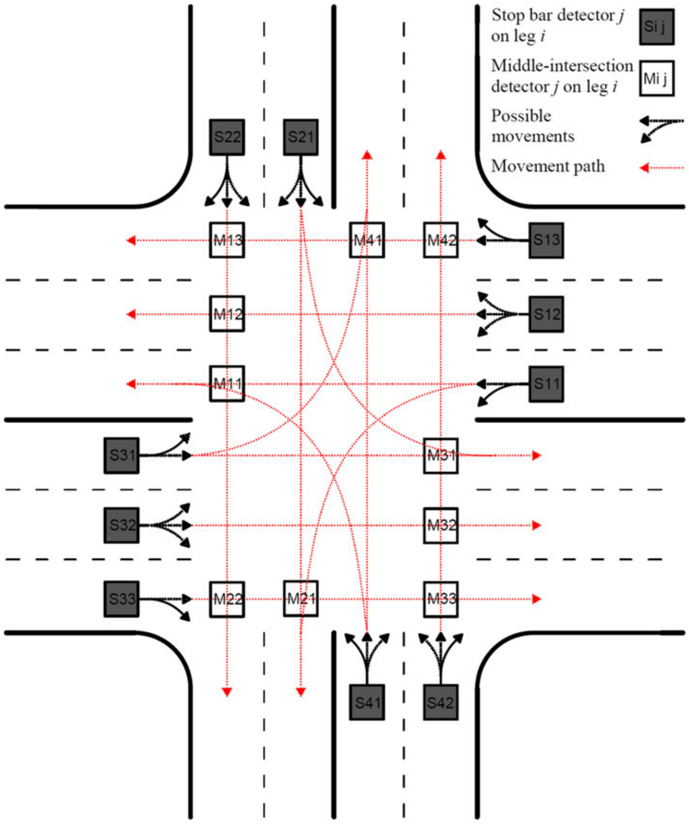

Figure 6. Mid-intersection detectors concept, Case 5.

the correct movements can still be extracted based on the sequence of activations. For example, in Figure 2, both WBL and EBL activate M_{21} and M_{41}. However, WBL first activates M_{41} and then M_{21} while EBL first activates M_{21} and then M_{41}.

This process should be repeated for all approaches and for all S_{ij} (stop bar detectors) activations.

There is a possibility, however, that some vehicles do not pass or do not activate all detectors (stop bar detectors and MIDs) along their path because of detection failure. At these situations, because of a lot of detectors and different activation sequences, most of the movements can be estimated based on the remaining detector activations. Flowchart of Figure 8 (failed activation algorithm) shows this process. After the process of obtaining data from the flowchart of Figure 7, all activations that are not related to S_{ij} activations will be transferred to failed activation algorithm (Figure 8). In this flowchart, based on the sequence of detector activations, an appropriate movement would be assigned to a sequence of activations. If no logical sequence can be extracted, then one count would be divided between all movements that may have activated the detectors based on the proportions of previous counts. For example, if one activation of M_{41} at the time of eastbound and westbound green remains undetermined, then one count can be shared between WBT, WBL, and EBL based on their previous counts. Suppose up to now the total numbers of counts for these movements are 300, 600, and 100, respectively, then 0.3, 0.6, and 0.1 would be added to counts of these movements, respectively.

3. SIMULATION AND CASE STUDY

Many modern controllers are capable of storing high-resolution data from detectors. This high-resolution data includes time of detector activations and the state of the signal at that time. Figure 9 shows a sample of high-resolution data obtained from a controller. However, because the MID concept has not been practiced yet, it is not possible to analyze it without simulation.

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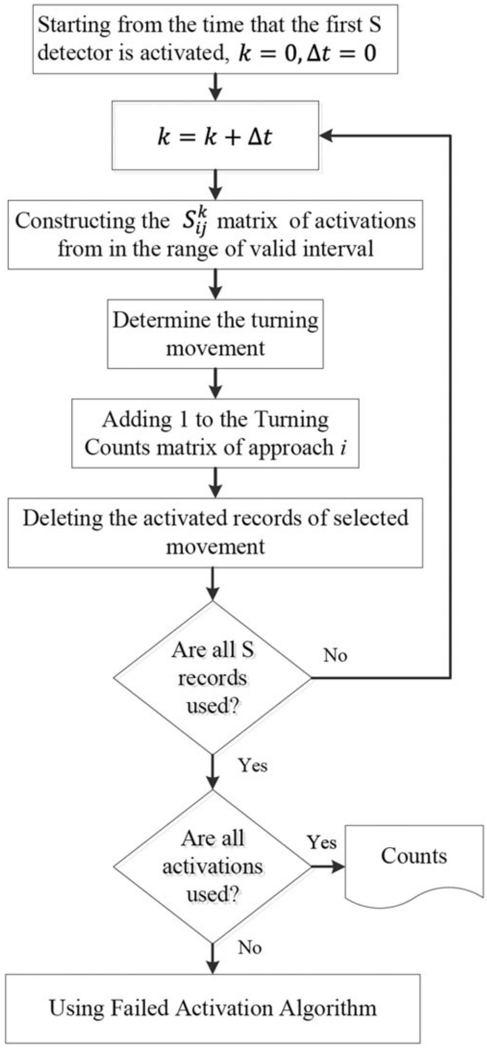

Figure 7. Obtaining counts from mid-intersection detectors.

A simulation was performed for the intersection at Oddie Boulevard and Sullivan Lane in Reno, Nevada (Figure 10) in VISSIM (a simulation software by PTV Group). All the intersection left turns are permitted. Simulation turning volumes are shown in Table I.

In VISSIM, because each MID covers several movements, a separate detector was placed on each movement, and then all movements at each location were combined. Simulation runs under ideal situations and cannot simulate different problems related to loop detectors. To make the simulation realistic, some noises (errors) were entered into the data randomly. These noises represent a variety of problems such as a detector's failure to detect any movement, double detecting of a single vehicle, and detectors that may be out of service. Also, the vehicles will not always make turns along the standard turning path, where MIDs are located, and they can miss the MIDs if they make a shaper or bigger turn. An algorithm was developed to enter all these noises into the data set. Each data set has been produced with a different probability of noise. For example, a data set with a probability of 5% noise means 5% of activations were wrong. The noises were randomly added to the data set. Using this algorithm, a percent of the activations were selected randomly. Then, a random percentage of selected activations were removed from the data set, and the rest of selected activations were doubled. Table II shows a sample of this data set. To enter noises into simulation data, it should be known how many activations are incorrect under normal operations at a real intersection, or in other words, what is the overall accuracy of detectors. For this purpose, another study was performed at the intersection of

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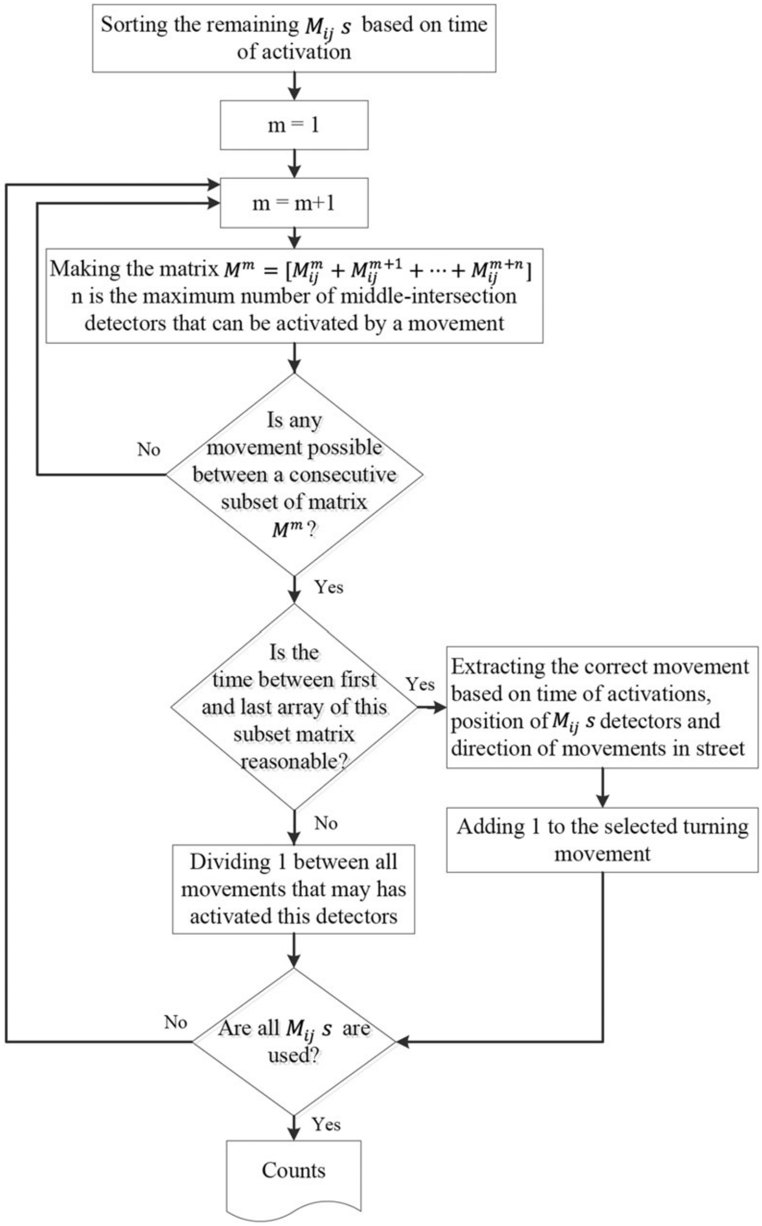

Figure 8. Failed activation algorithm.

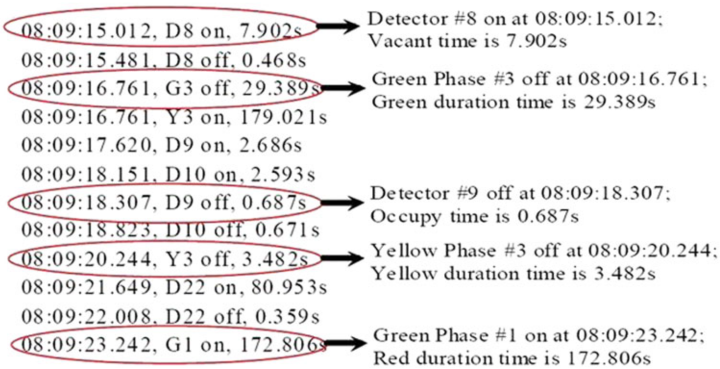

Figure 9. High-resolution data.

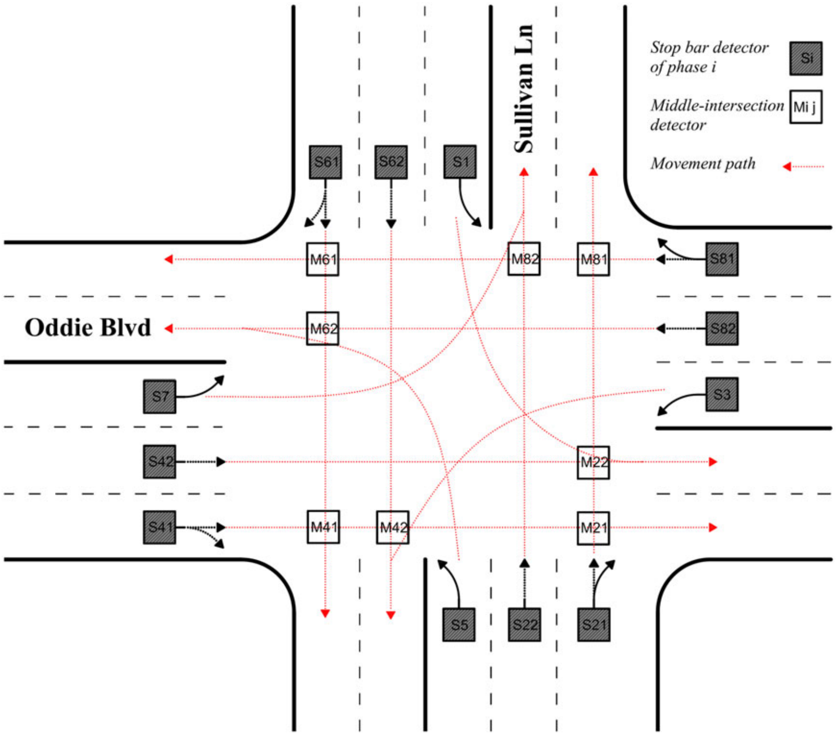

Figure 10. Case study at intersection, Oddie Blvd and Sullivan Ln in Reno, NV, Case 6.

Kietzke Lane and Moana Lane in Reno, Nevada. Figure 10 shows the accuracy of detectors in this intersection in terms of Mean Absolute Percent Error (MAPE) (see Equation 5).

$$MAPE(\%) = \frac{\sum_{i=1}^{n} \left| \frac{D_i - B_i}{B_i} \right|}{n} \tag{5}$$

where:

MAPE Mean Absolute Percentage Error
D_i the detector data value
B_i the reference (base) data value
n the total number of intervals

As it is evident in Figure 11, stop bar detector counts are unreliable because there are MAPEs more than 35%. The reason behind these high errors is the way that detectors are wired to the controller. Loops are spliced together and then two wires go to the controller cabinet. This structure is good enough for intersection controlling but reduces the accuracy of counts significantly. Based on the study done on real world detector accuracy, noises up to 40% were entered for simulation stop bar detectors. However, MIDs can produce a much lower error rate. The ITE report [15] concludes that if loop detectors are placed and wired properly, their counts would be “Excellent”, which means that counts

Table I. Turning volumes.

Street	Direction	Left turn	Through	Right turn
Oddie Blvd	EB	90	820	50
Oddie Blvd	WB	35	165	35
Sullivan Ln	NB	80	200	35
Sullivan Ln	SB	50	125	40

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Table II. A sample of VISSIM output for phase 4.

SG4*	S41**	M41***	M42***	M43***	S42**	M22***
I	.	.	.	.	.	.
I	.	.	.	.	.	.
I	.	.	.	.	.	.
I	.	.	.	.	.	?
I	.	.	.	.	.	.
I	.	?	.	.	.	.
/	.	.	.	.	.	.

*This column refers to state of signal; "|" means green, "/" means yellow, and point means red.
**These columns refer to state of stop detectors; "?" means activation, and point means no activation.
***These columns refer to state of MIDs; "?" means activation, and point means no activation.

tend to have an error of less than 5%. Some other common practices have "Good" and "Fair" accuracy, which mean 10 and 25% error, respectively. Based on these numbers, noises with a probability of 5, 10, and 25% were entered into the MIDs data set. Then, data extraction algorithms were applied to these data sets to evaluate the ability of MIDs under different conditions.

To compare MIDs with departure detector configurations, another case was defined for the same intersection. In this case, instead of MIDs, departure detectors were placed at the beginning of exit lanes. Then, the same levels of noise were also considered for this case. The same process was applied for Cases 1 to 5 (Figures 2–6). The next section compares and analyzes the results of MIDs accuracy with departure detectors.

4. RESULTS

Figure 12 summarizes the results of estimating counts from MID placement configuration and its equivalent departure detector configuration. When all detectors are perfect, two placement configurations produce almost 100% accuracy. However, when detectors work similar to detectors in the field (i.e. with errors including failure to detect or inaccurate counts because of splicing the stop bar detectors), MID configuration produce better counts. The reason for better accuracy of MID configuration is because of more detectors for each movement. As a result, if one detector fails to detect a vehicle, there is still a good chance another detector will sense it. The differences between cases are because of the number of MIDs needed for different movements. For example in Case 1, all movements are detected by two MIDs (note that in departure detectors all movements are always detected by only one detector, if detector does not fail to detect), while in Case 2, northbound and southbound through movements are detected by three MIDs, east bound and west bound right lanes through are detected by two MIDs

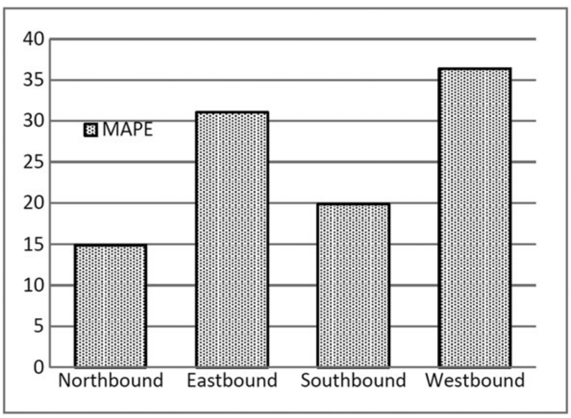

Figure 11. Average MAPE of detectors (stop bar) in the field, Reno, NV.

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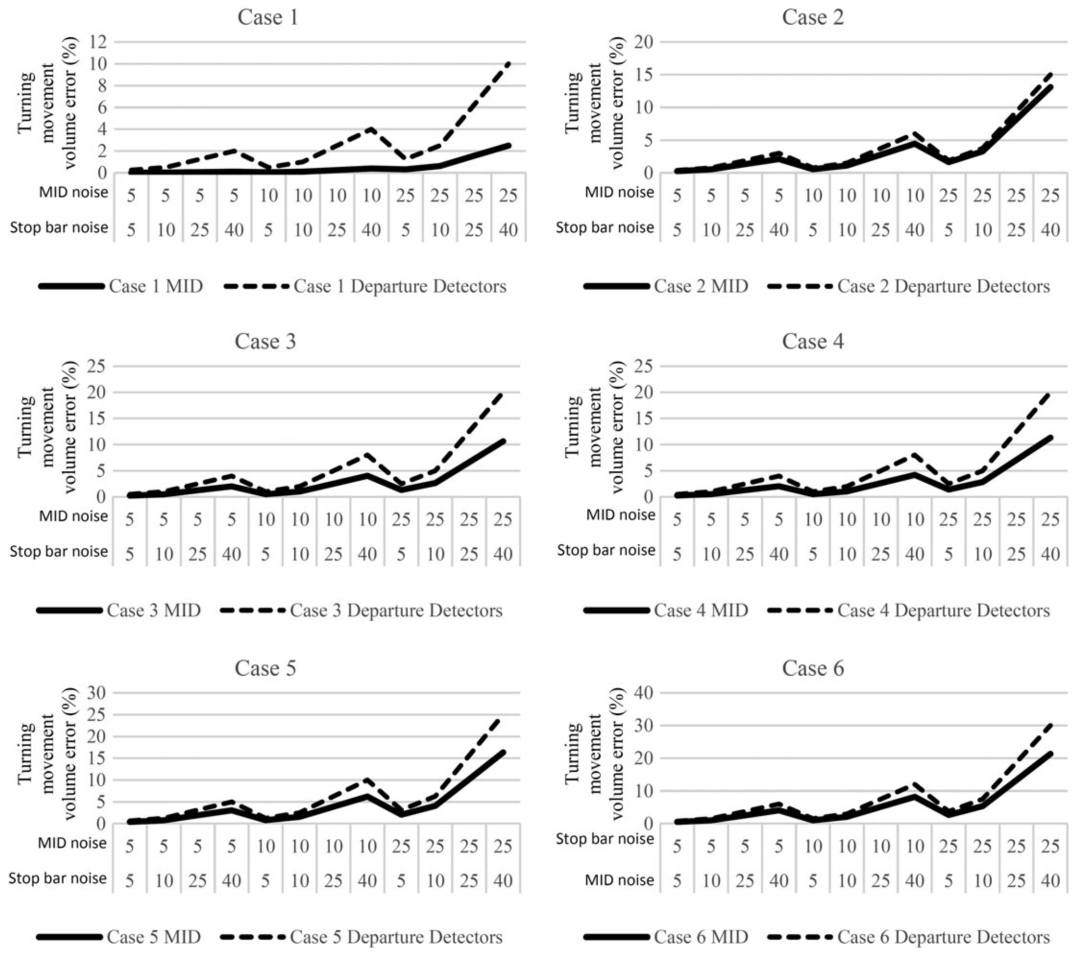

Figure 12. Count errors at MID and departure detectors configurations.

and left lane through movements are detected by one MID. These differences cause different errors for movements with different number of MIDs.

Note that Figure 12 shows only the improvements of MIDs over departure detectors regarding the first problem (i.e. when departure detectors fail to detect). There are some cases where departure detectors are not able to produce enough equations, and therefore, there is not a straightforward method for estimation of the counts. This figure does not reflect MID's improvements for this problem.

In Figure 12, each diagram shows 12 different conditions regarding the stop bar and MID noises. For example in Case 1, when the stop bar and MID noises are both 5%, estimated turning volume error is almost zero for both MID and departure detector configurations. On the other end of this diagram, when MID and stop bar detector noises are 25 and 40%, respectively, the errors of estimated turning volume of MIDs and departure detectors are 2.5 and 10%, respectively. Figure 12 shows that especially when detectors are not accurate (i.e. the noises are high), MID configuration can have up to four times less errors compared to departure detectors. The improvement of MID configuration over departure detector configuration is from 0.1% in Case 2 with 5% noise for both stop bar and MID detectors, to 9.4% in Case 3 with 40 and 25% noises for stop bar and MID detectors, respectively. Note also, as it was stated previously, that it is only one of MID's advantages, and this simulation does not reflect other advantages of MIDs including giving more equations for unknown movements, especially when there are shared lanes or permitted left turns. Another advantage of MIDs compared to departure detectors occurs when permitted left turns are trapped in the middle of the intersection after the termination of green time. Using MIDs, these vehicles can be detected and safely exit the intersection before the end of their green time.

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5. CONCLUSION

Loop detectors are the most common practice for obtaining data at intersections. In spite of many advantages, they have some drawbacks, including the fact that multiple detectors are usually required to monitor a location. The current practice in many cities is to install four consecutive loop detectors per lane, or two at the stop bar and one as an advanced detector. In some cities, there are also departure detectors. All these configurations have some practical problems and are not able to produce reliable turning counts. In this paper, a new placement configuration has been proposed and named MID. MIDs can produce more accurate and reliable data for generating intersection O–D counts because they provide more detector activation per movement. While in departure detector configuration, there is only one activation per movement in addition to the stop bar detector activations, by using MIDs, it is possible to increase the number of detector activations per movement up to the number of perpendicular lanes plus one. With increasing the number of activations per movement: (i) the number of equations would be more than the number of unknown movements; (ii) if some of the detectors fail to record a vehicle, there is the possibility that the vehicle be recorded by other detectors.

Also, MIDs can solve another problem when left turns are permitted. Drivers that pass the stop line beyond a detection zone and wait for a gap in the opposing traffic may be left undetected if a gap does not occur or a vehicle ahead prevents the turn. In this case, the controller may skip the turn arrow in the next cycle because the vehicle is positioned ahead of the sensor's detection zone. Some agencies extend the loop beyond the stop line to prevent this situation; however, it may interfere with other movements. These left turn movements can be detected using MID.

MIDs may have some practical issues however. First, it is possible for vehicles to not follow the track where MIDs are located. This is especially important to consider if the intersection has one left turn into a multiple lane street. For example, if left turn enters a three lanes street, some drivers do not stay in the lawful lane (the left lane) of the three lanes street. Another issue is that with regular inductive loop detectors, an entire lane needs to be closed to complete maintenance on one detector. For MIDs, a larger part of the intersection needs to be closed in order to maintain a detector. This layout also needs more post data processing to extract turning movements.

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