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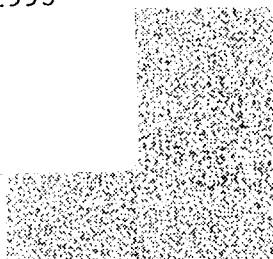
UNIVERSITY OF MINNESOTA

**ENERGY CONSERVATION
THROUGH VIDEO IMAGING
AND ON-LINE TRAFFIC
MONITORING**

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Civil and Mineral Engineering**

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**ENERGY CONSERVATION THROUGH VIDEO IMAGING AND
ON LINE TRAFFIC MONITORING**

FINAL REPORT

By

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1. INTRODUCTION

Measures Of Effectiveness (MOE's) is the Traffic Engineer's collective term for a number of indicators that describe the traffic situation within a stretch of a roadway segment. These indicators measure how efficiently traffic is moving (or in some cases not moving) along the road in question. By doing 'before' and 'after' MOE studies, Traffic Engineers can assess the effects of improvements such as changes in the road geometry, signal optimization, introduction of traffic control devices and other traffic management schemes. MOE's are particularly useful for evaluating the effectiveness of traffic control strategies, so that the most effective strategy can be implemented.

Recent studies indicate that in the U.S, the traffic situation will deteriorate. Traffic volumes are expected to increase, by as much as 45 percent by 2005 [1]. Unless appropriate measures are taken, delays and travel times will most likely increase, not only during rush hours, but during all times of the day. A recent study by the Minneapolis Star Tribune newspaper [2] asked people to characterize driving conditions during rush hour. People generally felt the situation was much worse compared to five years ago. Some described the situation as "very stressful", "awful", and "a major inconvenience", even though congestion levels in Minneapolis are relatively mild compared to Chicago, Los

Angeles and New York.

It is up to Traffic Engineers to improve traffic control strategies. Accurate estimates of Measures of Effectiveness will aid in developing and evaluating those strategies. When traffic control strategies allow smooth traffic flows, travel times become shorter, pollution levels and fuel consumption decrease and last but not least, travelers will find their trips more enjoyable.

Reliable and accurate estimates of Measures of Effectiveness at intersections or highway segments are not easily calculated. Many MOE collection methods compute only rough estimates of these MOE's, resulting in inaccurate traffic evaluation and control strategies. In many cases, the MOE data collection process involves a great deal of tedious (and therefore error prone and expensive) manual labor. As a result, performance monitoring is rarely carried out, and is usually initiated only after a problem persistently occurs.

This report describes a 'fully automated', simple and practical approach for extracting (in real time) sufficiently accurate measurements of the most common traffic parameters and MOE's such as volumes, speeds, stops, delays, queue lengths, travel times and Level of Service, at intersections and highway segments. Then, those estimates are used to compute reasonable estimates of fuel consumption and pollution levels such as nitrous oxide, hydrocarbons and carbon monoxide emissions.

To collect the necessary real time vehicle detection data required by the MOE algorithms, a machine vision system called Autoscope is utilized. The Autoscope "machine vision system for vehicle detection consists of an electronic camera overlooking a long section of the roadway; from the images received by the camera, a microprocessor determines vehicle presence or passage and derives other traffic parameters" [3]. In order to implement and test the MOE algorithms described in this report, an already existing Autoscope data collection program was enhanced. Specifically, the MOE algorithms were coded, the capability to display the MOE data numerically or graphically in real time, and the capability to save the MOE data to a data file for later analysis was implemented, using the Windows 3.0 Software Development Kit.

This report presents and proposes the use of the Autoscope and its accompanying Autoscope vehicle detection and MOE data collection programs as a viable option for real time traffic monitoring and analysis of intersections and highway segments.

The MOE algorithms presented in this report were tested at three test sites; the first is a three-lane approach at an intersection in northwest Minneapolis (T. H. 65 & 53rd Street), the second at Interstate highway 35W at 26th Street, the third at Interstate highway 35W at Lyndale Ave in Minneapolis. The MOE data obtained from the test sites was validated using manual methods. The results are encouraging,

showing an average error of about 10 percent in MOE estimates obtained during congested traffic flow conditions.

In section 2, basic traffic flow definitions and notational conventions used in this thesis are provided. In section 3 a background to the MOE collection problem and current MOE collection techniques are presented. In section 4 the current vehicle detection instrumentation available to Traffic Engineers is briefly described. In section 5 the components of the vehicle detection and MOE collection instrumentation presented in this report are discussed. In section 6 the proposed MOE collection algorithms and methodology are presented. In section 7 the testing and validation results are presented. Finally, in section 8 conclusions from the test results are presented.

2. BASIC DEFINITIONS AND NOTATION

Roadway Segment. A roadway segment is a section of roadway in which traffic parameters and MOE's are measured. The roadway segment may be part of an intersection approach or be a segment of a highway. The length of the roadway segment is denoted by L .

Time Step. A time step is defined as an interval in time in which vehicle detection data is being collected. Time is discretized into sequential time steps of equal length. Time steps are denoted by t . At intersections, a time step less than the intersection cycle length is appropriate for measuring MOE's using the methodology presented in this paper.

At highway segments, the duration of a time step is usually anywhere from 30 seconds to 15 minutes.

Lane. The MOE collection models described in this report collect data on a per-lane basis. Lanes are denoted by j .

Detector. A detector is a device used for collection of vehicle detection data, such as passage (counts), presence (time over a detector) and (point-measured) speeds. A detector can be either **ON** (a vehicle is over the detector) or **OFF** (no vehicle is over the detector). Detectors are denoted by d .

Volume. Traffic volume is the total number of vehicles that pass a point on a roadway during a given time step [4]. Volume is denoted by V . The traffic volume accumulated by detector d in lane j during time step t is therefore $V_{d,j,t}$.

Input Volume. Input volume is the traffic volume that entered a roadway segment during a time step. The input volume is measured by detectors at the upstream end (or 'input end') of the roadway segment.

Output Volume. Output volume is the traffic volume that exited a roadway segment during a time step. The output volume is measured by detectors at the downstream end (or 'output end') of the roadway segment.

Queue Length. Traffic queue length is the number of vehicles queued in a lane at an intersection. Queue length is denoted by Q .

Primary Stop. A primary stop is defined to be the first stop by a vehicle as it enters (or forms) a queue at an

intersection [5]. Primary stops are denoted by P.

Delay. "Delay is the time lost by a vehicle due to causes beyond the control of the driver" [4]. Such causes include the interference of other vehicles, road construction, and delay caused by traffic control devices such as entrance ramp signals or stop signs. Traffic Engineers distinguish between many forms of delay, such as stopped delay, travel time delay, and operational delay [4]. In this report, delay (of any kind) is denoted by D.

Total Travel. Total travel is the total distance traveled by all vehicles within a roadway segment during a given time step. Total travel is denoted by TT.

Total Travel Time. Total travel time measures the total time spent by all vehicles inside a roadway segment during a time step (including stopped time and other causes of delay) [1], [4]. Total travel time is denoted by TTT.

Fuel Consumption. Fuel consumption is the total amount of fuel consumed (in gallons) by vehicles within a roadway segment, during a time step. Fuel consumption is denoted by FC.

Emissions. Emissions is the total amount of nitrous oxide (NOX), carbon monoxide (CO) and hydrocarbons (HC) in grams, emitted by vehicles inside a roadway segment during a time step.

Space Mean Speed. Space mean speed measures average travel speed [6]. The space mean speed measured at a point is given by

$$\overline{S}_{d,j,t} = \frac{n}{\sum_{k=1}^n \frac{1}{S_k}}$$

where n is the number of vehicles traveling over speed trap d in lane j during time step t , and S_k is the speed of vehicle k [7]. The term space mean speed (which is the speed measure used most frequently in Traffic Engineering circles) refers to the fact that the speeds are measured according to how much time each vehicle spends within a short section (or space) of roadway. Alternatively, space mean speed can be computed from $TT_{j,t}/TTT_{j,t}$ [4], [7]. Speeds are denoted by S .

Level of Service. Level Of Service (LOS) is a widely used Traffic Engineering concept developed by the Federal Highway Administration. LOS estimates the driving conditions within a roadway segment by assigning the roadway segment a 'grade' from A to F [8].

3. TRADITIONAL MOE ESTIMATION PROCEDURES

The following section gives an overview of how MOE's are traditionally estimated and collected. A short section also reviews the advantages and disadvantages of using traffic simulation software programs to extract MOE's.

3.1 INTERSECTION STOPS, DELAYS AND QUEUE LENGTHS

It is important to find an estimate of average vehicle delay at intersections, since one of the main objectives of the intersection signal timing plan is to reduce average vehicle delay [4]. There are many methods that estimate

intersection delay, for instance Webster's method, which uses saturation flows, effective green times and cycle lengths [4]. One of the simplest methods is a manual method. An observer simply samples the intersection queue lengths periodically, typically every 15 seconds [6]. From that data, a queue length versus time plot can be drawn and delay can be computed by manually or numerically integrating the area under the curve (an example queue length vs time curve is shown in figure 1). Care needs to be taken so that the sampling interval is not a multiple of the intersection cycle length, since then the same portions of the signal cycle would be sampled.

Similarly, the cumulative number of vehicle stops during the study period can be collected by means of manual counting. This data is useful for determining the percentage of vehicles that are forced to stop when they enter the intersection roadway segment.

A problem with all manual data collection methods is that the measurements cannot be collected for continuous, extended periods of time.

3.2 HIGHWAY SEGMENT DELAYS AND TRAVEL TIMES

Travel times are important to measure, most importantly from a safety standpoint. One way of estimating highway travel times is to use a test vehicle that moves along the traffic stream in a highway segment, traveling at a speed that the driver estimates to be the average travel speed of the surrounding traffic - the so called floating car technique

[4], [6]. A disadvantage of this method is that in order to acquire reasonably accurate travel time data, several vehicle test runs for each level of congestion are required. Vehicle travel times can also be manually recorded by observers positioned at the input and output end of the roadway segment. The observers note the time when a vehicle enters and leaves the roadway segment, and also record the last three digits in the license plate number. In this way, a record of vehicle travel times can be created. The average of the vehicle travel times is then a measure of the average travel speed inside the roadway segment. This method is fittingly called the license plate method [6]. The actual vehicle travel times can be compared with 'ideal' travel times, recorded during free flow conditions. The actual travel times minus the 'ideal' travel times then represent vehicle delay (actually travel time delay) [4]. Obviously, for both these data collection methods, the amounts of manual effort and costs involved are considerable.

3.3 TOTAL TRAVEL

Total travel can be measured manually at both intersections and highway segments by counting the number of vehicles traveling through the roadway segment (using for instance loop detectors or manual counts), and then multiplying that number by the length of the roadway segment. Formally,

$$TT_{j,t} = V_{j,t} * L$$

where $TT_{j,t}$ is the total travel over lane j at time step t , L is the length of the roadway segment under consideration, and $V_{j,t}$ is the time step output volume from lane j .

3.4 TOTAL TRAVEL TIME

As previously mentioned, vehicle travel times at intersections and highway segments over a time step can be obtained by using a test vehicle that 'floats' with the traffic stream, traversing the same roadway segment several times. The average of the test vehicle travel times is then a measure of the average travel time for the roadway segment. The average travel time can be multiplied by the number of vehicles that travel through the segment, to obtain total travel time [4]. Formally,

$$TTT_{j,t} = \overline{T}_{j,t} * V_{j,t}$$

where $\overline{T}_{j,t}$ is the average test vehicle travel time during time step t , and $V_{j,t}$ is the output volume from lane j of the roadway segment. TTT can also be estimated by plotting the total number of vehicles within the roadway segment over time, and integrating the area under the curve. At intersections, such density data can be obtained by means of manual counting [6]. At highway segment locations, a sequence of aerial photographs of the highway section, taken at short intervals

may be used [7], [9].

3.5 FUEL CONSUMPTION

Fuel consumption estimates are valuable indicators of the pollution levels at intersections and highway segments (obviously, the goal is to minimize total fuel consumption along the road in question). A number of factors affect the fuel consumption of an individual vehicle, among them the engine type, vehicle year and size, aerodynamic properties and the presence or absence of air conditioning [9].

Fuel consumption can be measured using simulation programs. For instance, Kronos (a highway simulation program developed at the University of Minnesota) is one such simulation program [10]. SOAP-84 is another simulation program that measures intersection fuel consumption [11].

3.6 VEHICLE EMISSIONS

Vehicle emissions are also important indicators of roadway pollution levels (most importantly for human safety and health reasons). Vehicle emissions have three main components; carbon monoxide, hydrocarbons and nitrous oxides. While not directly fatal to humans, vehicle emissions contribute greatly to the formation of smog and the further depletion of the ozone layer [9].

Vehicle emissions can be measured using simulation programs, or be measured directly at a site.

3.7 LEVEL OF SERVICE

Intersection LOS (as given by the Highway Capacity

Manual, [8]) is based solely on average vehicle stopped delay for the analysis period. The HCM recommends a 15-minute period. Level of service A is obtained when most vehicles approaching the intersection arrive during the green phase. In this case the vehicles rarely stop, and incur very low delays. LOS F occurs when the travel demand exceeds the service capability of the intersection. Stops are frequent and average delays are typically very high (in excess of 60 seconds). The common practice is to measure LOS during the most congested period (during AM or PM rush hour), to get a worst case scenario of the driving conditions at the intersection. The LOS measure (along with other measures) can then be used to calculate the intersection signal timing plan. The criteria for determining intersection LOS are shown in figure 2. Usually intersection LOS is measured using the HCM intersection operational analysis method [4], [8]. The operational analysis method uses road geometry, phasing and volume information (among other things), to calculate intersection LOS through a series of worksheets.

Highway segment LOS is based on density (given in passenger cars per lane per mile) [8]. Highway LOS is commonly measured using one-hour data. LOS A represents uninterrupted flow. Each vehicle has room to maneuver freely, and the driver can select the speed at which to travel. In contrast, LOS F corresponds to a situation where the demand for travel exceeds the service capability of the roadway segment. Queues form,

maneuvering becomes difficult, and speeds are low. The criteria for determining highway segment LOS are shown in figure 3. Note that density is measured in passenger car equivalents per mile per lane. The term passenger car equivalent (PCE) is an adjusted volume measure that takes into account the presence of heavy vehicles (such as trucks, buses and recreational vehicles) in the traffic stream. PCE converts the number of heavy vehicles into a corresponding number of passenger cars (ie when the heavy vehicles traveled through the roadway segment, how many passenger cars would have to travel through the segment in order to have an equivalent effect on the traffic stream). Heavy vehicles always correspond to at least one passenger car.

Highway Level of Service is typically measured using the HCM highway operational analysis method, with which, given (among other things) road geometry information, traffic volumes and traffic composition, it is possible to estimate LOS through a series of worksheets [4], [8].

3.8 TRAFFIC SIMULATION PROGRAMS

Traffic simulation programs is software used in non real time to predict and simulate traffic conditions at roadway segments, using previously collected test site data, road geometry information, and other information (such as signal cycle information and traffic composition). Traffic simulation programs use mathematical modeling to compute traffic movements over time.

By varying the test site input parameters (such as traffic volumes, lane widths or the signal phasing), and then running the simulations, the Traffic Engineer can make judgements of current or future driving conditions at a site. Some traffic simulation programs also have the capability to optimize certain parameters, such as the signal cycle lengths. Some common traffic simulation programs are Transyt-7F (used for intersection network planning and control), Passer-II (also used to simulate intersection networks), Soap-77 (used at isolated intersections) and Kronos (a highway simulation program).

While simulation programs certainly have an important role to fill in traffic planning and control, their effectiveness for current-situation test site analysis is more questionable, since they cannot (by definition) analyze real time data obtained during a continuous, extended period of time. In other words, the simulation results only show a 'snapshot' of the traffic conditions resulting from a specific pattern of vehicle arrivals and departures. Obviously, there are innumerable such patterns. On the other hand, real time traffic monitoring systems can be used to continuously monitor a roadway segment for weeks or even months, thereby giving a more complete picture of the traffic patterns over a long period of time.

Simulation programs tend to be time consuming (both in terms of computer time and manual effort involved) and also

somewhat unwieldy to use and to understand.

4. EXISTING VEHICLE DETECTION INSTRUMENTATION

In this section, the most commonly used vehicle detection devices are presented. Some problems concerning the use of those detection devices are also discussed.

Loop detectors (currently the most popular choice for vehicle detection) are permanent features of the roadway. Essentially, a loop is "one or more turns of insulated loop wire wound in a shallow slot sawed in the pavement. When a vehicle passes over the loop or is stopped within the loop it decreases the inductance of the loop" [12]. Vehicle passage or presence can then be detected.

Another type of vehicle detector is the magnetic detector probe. The magnetic detector probe is a cylindrical device placed in the pavement. It can only detect passage (count) data and is therefore used only in special cases, since presence data is almost always required at a detector location.

A third type of detector is the magnetometer probe, which is a small cylinder "embedded vertically in the surface of the roadway" [12]. Magnetometer probes are not sensitive to pavement problems and can be used instead of loops at detector locations with poor pavement structure.

Other detector types include radar detectors and ultrasonic detectors. These detectors are in many cases in a research development stage and are not widely used for Traffic

Engineering purposes.

In general, a problem with detectors embedded in the roadway surface is that once they are placed in the pavement, they are not easily removed or repaired. These detectors are basically permanent features of the roadway. The very installation of such detectors causes irreparable damage to, and premature aging of the pavement. FHWA studies have also shown operational problems with loops, such as frequent partial or total failures to detect vehicles. One study found around 30 percent of the loop detectors used in the study to be only partially functional or failed at any given instance in time [13]. Probably the greatest disadvantage of the aforementioned vehicle detection devices is the limitation of monitoring only a single point of the roadway. Most MOE's require an area to be monitored for their proper measurement.

As for the reliability and accuracy of the Autoscope video detection technology, studies show similar or better detection accuracy and improved reliability compared to loops (see [3] and [14]), although the use of a video camera introduces problems of its own (see [15] and section 5.4 of this report).

5. PROPOSED INSTRUMENTATION

In this section, the proposed vehicle detection and MOE collection devices are briefly presented. For a more thorough introduction to the Autoscope, see [3], [14] and [15]. Detector layouts (and some of the problems involving detector

layouts) are also discussed.

5.1. AUTOSCOPE

The Autoscope is a video detection device developed at the University of Minnesota. The Autoscope "can detect traffic in many locations (i.e., multiple spots) within the camera's field-of-view. These locations are specified by the user in a matter of minutes using interactive graphics and can be changed as often as desired. This flexible detection placement is achieved by placing detection lines along or across the roadway lanes on a TV monitor displaying the traffic scene. Therefore, these detection lines are not physically placed in the pavement but only on the TV monitor. Every time a car crosses these lines, a detection signal (presence or passage) is generated by the device" [3].

In other words, when Autoscope detects a vehicle entering or leaving a detection line or a speed trap, it generates a detector ON or OFF signal that can be sent over a serial communications line to an Autoscope data collection program (described in the next section).

Autoscope also computes individual vehicle speeds, and sends periodic data reports which contain the total volume, average speed (time mean speed), the total occupancy, and vehicle classification counts per detector for each time step. Commonly used time steps are 30 seconds, 1 minute or 5 minutes. Note that the traffic parameters are measured over an area of the roadway, rather than a point.

The video input to the Autoscope does not necessarily have to originate from a live camera feed. Consequently, previously recorded video tapes can be used to generate real time Autoscope data. For the purposes of this report, the testing and validation of the MOE collection algorithms was accomplished using sequences from two-hour video tapes previously recorded at the test sites.

An Autoscope detector layout program running under Windows allows the user to draw detectors and speed traps anywhere on the video image using a mouse. The detector layout is then saved to a file which can be sent to the Autoscope, allowing the Autoscope to detect vehicles using the new detector layout within a matter of minutes. This great flexibility in detector placement means that the user can experiment with several different detector layouts to quickly find the optimum layout for the particular field of view of the camera. Figures 4, 5, and 6 show examples of detector layouts at intersections and highway segments. More specifically, they are the layouts for the three test sites used for this report.

5.2. THE SUPERVISOR

The Supervisor is a data collection program running under Windows. It is designed to receive and analyze Autoscope data. In short, the Supervisor takes Autoscope data, and displays the data numerically or graphically. The Supervisor also has a limited capability of analyzing Autoscope data in

order to display speeds, volumes, occupancies (the percentage a detector is ON, or occupied, during a time step), flows (vehicles per hour) and average time headways (the average distance in seconds between successive vehicles). The Supervisor can save all Autoscope detection data to a text file for later analysis. The Supervisor can also be used to download and upload detector layout files to and from the Autoscope.

5.3. IMP¹

The IMP (Imperative Monitor of Performance) is an enhancement to the Supervisor developed by the author of this report. The IMP was designed to further analyze Autoscope data to extract MOE's that are useful for monitoring flow performance at intersections and highway segments.

IMP calculates the following Measures of Effectiveness at an intersection (for the section of roadway being analyzed, per time step per lane): stopped delay (in vehicle-seconds), total travel time (in vehicle-seconds), total travel (in vehicle-feet), the total number of primary stops, queue lengths, total fuel consumption in gallons, total hydrocarbons, carbon oxide, and nitrous oxide emissions (in grams), and intersection Level Of Service.

The IMP calculates the following MOE's at a highway

¹ The Random House Dictionary defines IMP to be "a little devil or demon" or "a mischievous child". Although his parents might claim the author possessed some of the qualities associated with an IMP in his youth, the reader can be assured the IMP presented here certainly does not exhibit any impish qualities.

segment (for the section of roadway being analyzed, per time step per lane): total travel time (in vehicle seconds), total travel (in vehicle-feet), total delay (in vehicle-seconds), total fuel consumption (in gallons), highway Level of Service, and total HC, CO and NOX emissions (in grams).

The IMP was designed to be as independent of the Supervisor as possible (in fact, in Windows terminology it is a separate object, or window). It is convenient to think of the Supervisor and the IMP as separate programs, which only share access to the Autoscope. The Supervisor has the ability to start or terminate the IMP program; the Supervisor's only other responsibility is to ensure that the IMP receives Autoscope data (such as detector ON/OFF signals), when it arrives through the serial communications port.

The IMP has three modes of operation. In CONFIGURE mode the user can create and/or read in an IMP configuration file, which describes the current detector configuration (such as the ordering of the detectors in each lane), and the default values of various IMP operational parameters. In this way, the user can create an IMP configuration file that is coupled with an Autoscope detector layout file, and then quickly recall that configuration file at a later analysis situation, without having to repeat the (sometimes) tedious procedure of restoring all the IMP parameters to their desired values. A description of the IMP operational parameters is given in Appendix A.

In REAL-TIME mode, the IMP (with the help of the Supervisor) can collect and analyze Autoscope data in real time. The various MOE's can be depicted numerically or graphically on the screen and also periodically be saved to an IMP data file. In DATA-ANALYSIS mode, the IMP can recall a previously saved MOE data file and display the data graphically for analysis purposes.

5.4. AUTOSCOPE DETECTOR LAYOUTS

This section discusses how to lay out detectors at intersections and highway segments in order to obtain optimum Autoscope and IMP performance. The section also reviews some of the problems associated with detector layouts that can negatively affect Autoscope performance.

5.4.1 INTERSECTION DETECTOR LAYOUTS

At an intersection, the IMP directly measures the MOE's by using the information from a grid of vehicle detectors placed along the intersection approach, as shown in figure 4. A minimum of two detectors per lane are required (one at the stopline, and one as a call detector at the upstream boundary of the section of roadway being analyzed). For greater accuracy in calculating queue lengths, stops and delays, it is recommended to use 3-4 detectors per lane, evenly spaced along the approach. The call detectors and stopline detectors in each lane are used to measure vehicle input to and output from the roadway segment.

At the intersection test site used for this report, the

camera was mounted at an angle with respect to the approach that was monitored, so that tall vehicles traveling in the leftmost lane also overlapped detectors in the middle lane (so-called occlusion), causing false detections and therefore inaccurate MOE estimates. However, heavy vehicles (including buses) accounted for only 2 percent of the total traffic volume at the intersection test site. To alleviate the problem of occlusion at future locations, it is recommended that the camera (if possible) be placed at a more central location of the intersection, so that vehicles do not seem to travel at an angle with respect to the approach(es) being monitored.

Another problem at the intersection test site (also partially due to the camera placement) was that at a distance, there was no vehicle separation visible on the video image. Consequently, the Autoscope detectors would tend to detect only platoons of vehicles. Possibly, the Autoscope detection performance can be improved by positioning the camera higher above the ground (at the test site, the camera was mounted 32 feet above the ground).

5.4.2 HIGHWAY DETECTOR LAYOUTS

At the highway test sites, detector layouts consisting of a combination of count detectors and speed traps should be used. The highway MOE collection algorithms require that each lane has at least two pairs of count detectors and speed traps, defining the boundaries of the section of roadway being analyzed. The detectors placed at the upstream and downstream

boundaries of the roadway section of each lane, are used to measure input to and output from the highway segment respectively, and the space mean speeds from the speed traps in each lane are averaged to obtain the lane space mean speed.

The highway detector layouts used for this report are shown in figures 5 and 6. Because of the camera angles at the test sites used for this report, occlusion was negatively affecting Autoscope performance. Low vehicle separation at a distance also caused missed detections.

6. PROPOSED METHODOLOGY

In the following section, the MOE collection algorithms used by the IMP program at intersections and highway segments are discussed in detail.

6.1 INTERSECTION DELAYS AND QUEUE LENGTHS

In essence, the intersection delay/queue length derivation algorithm presented here is a version of the general input/output model. This model defines a section of the roadway to be the current section of analysis, as shown in figure 4. For the purposes of the algorithm presented here, it is not recommended that the upper boundary of this roadway segment be more than 400 ground feet from the camera, since at that distance Autoscope performance seems to suffer in heavy congestion, due to low vehicle separation. Possibly, this distance can be increased by mounting the camera higher on the camera pole.

The general I/O model monitors how many vehicles enter

and exit the roadway segment in each lane, using the call detector to measure vehicle input and the stopline detector to measure output. The cumulative input (in vehicles) to the roadway segment can be denoted by I , and the total output by O . At any time the vehicle 'storage', or queue length, within the segment must be given by the difference, or $I-O$. If I and O are plotted over time, the area between the curves represents vehicle delay. Similarly, if queue length (the number of vehicles in the queue) is plotted over time as in figure 1, the area under the curve also represents vehicle delay (specifically stopped delay).

The algorithm presented here uses what can be described as a discretized version of the standard I/O model; a compartment model. If a grid of 4 detectors are placed in a lane, the space in between each pair of detectors could be called a compartment (see figure 7). The IMP compartment algorithm keeps track of how many vehicles are in each compartment and uses this information to compute stops, queue lengths and delays.

A minimum of two detectors per lane are required (one at the stopline and one at the upstream boundary of the roadway segment), which will create one compartment. The algorithm then works precisely as the standard input/output model. If three detectors are used, there are two compartments. In general, the number of compartments in a lane is equal to the number of detectors in the lane minus one.

Every time the call detector in a lane (the detector farthest from the stopline) turns ON, the vehicle count in the compartment immediately downstream of that detector (the compartment closer to the stopline) is incremented. Every time a detector between the call detector and the stopline detector turns ON, the vehicle count in the compartment upstream from it is decremented (if it is > 0), and the vehicle count in the compartment downstream of it is incremented (since the vehicle then physically traveled from the compartment upstream of the detector to the compartment downstream of the detector). When the stopline detector turns OFF, the stopline compartment vehicle count is decremented.

This process is described in figure 8, in which a vehicle is shown traveling through an intersection roadway segment. In stage 1, a vehicle is entering the roadway segment, and the vehicle count in compartment 3 is incremented. In stage 2, the vehicle enters compartment 2. The vehicle count in compartment 3 is then decremented and the vehicle count in compartment 2 is incremented. In stage 3, the vehicle is leaving the roadway segment, so the vehicle count in compartment 1 is decremented.

A compartment can have two possible states; it can either be QUEUED or NON-QUEUED. If the compartment is QUEUED, a queue of vehicles is contained within the compartment. The queue may be stationary or slowly moving. If the compartment is NON-QUEUED, no queue (or a fast-moving queue) of vehicles

is contained within the compartment.

Each time a vehicle enters the roadway segment being analyzed (a call detector turns ON), or leaves the segment (a stopline detector turns OFF), the state of each compartment in each lane is determined. The lane queue length is calculated by summing the number of vehicles in each QUEUED compartment in the lane; the time step delay is then computed numerically by integrating the area under the queue length vs time plot. Therefore, the current queue length and the delay in each lane is continuously available within the IMP program.

In fact, the compartment model can register the presence of SEVERAL queues within the roadway segment, since it will be known which COMPARTMENTS are in a QUEUED state and consequently contain a queue.

Note that the notion of vehicle length does not in any way enter into the queue length computations; it is simply a matter of counting the number of vehicles in each compartment. Note also that the compartment algorithm does not require any knowledge of the intersection cycle length or the intersection signal timing plan, nor does it require any interface to the intersection controller (in the future, the Autoscope will feature a controller interface).

Moreover, the compartment algorithm can manage large vehicles such as tractor trailers, since (at least as far as the algorithm is concerned) a vehicle is only present in one compartment at a time, so that a 50-foot tractor trailer which

physically occupies several compartments, will only be 'officially' located in the compartment it occupies that is closest to the stopline. In figure 9, a tractor trailer is shown traveling through an intersection roadway segment. In stage 1, as the tractor trailer enters the segment, the vehicle count in compartment 3 is incremented. In stage 2, as the tractor trailer enters compartment 2, the vehicle count in compartment 3 is decremented, and the vehicle count in compartment 2 is incremented. Finally in stage 3, when the tractor trailer stops at the stopline, the vehicle count in compartment 1 will have been incremented and the vehicle count in compartment 2 will have been decremented. Even though the tractor trailer is physically covering more than one compartment, the compartment algorithm records the correct vehicle count.

But how does a compartment become QUEUED? This is where the detector POLLING algorithm comes into place. The detector polling algorithm is invoked periodically by a Windows internal clock (or timer). It is the responsibility of the detector polling algorithm to check the state of each detector frequently (1-5 times a second), to determine if each detector is ON or OFF. The polling algorithm also keeps track internally of precisely WHEN each detector turned ON or OFF, to within a few milliseconds accuracy.

When a detector has been continuously ON for some user-specified amount of time, the compartment associated with that

detector is considered QUEUED, with a queue length equal to the number of vehicles in that compartment. In effect, the detector polling algorithm uses occupancy (time over a detector) and therefore vehicle speed, to classify the state of each detector and its respective compartment. Note that occupancy also is a function of vehicle length; therefore the threshold that determines when to put a compartment in a QUEUED state must be set carefully by the user, so that a long vehicle traveling slowly over a detector does not erroneously put the detector's compartment in a QUEUED state. Vehicle time over a detector, T , is given by

$$T = \frac{L_e}{S}$$

where S is the speed of the vehicle, and L_e is the effective vehicle length, which is approximately equal to the sum of the actual vehicle length and the real-world length of the detector [7]. As a worst case example, a 35-foot vehicle traveling at 10 mph over a 5-foot detector would then occupy the detector for approximately 2.7 seconds, suggesting a QUEUED threshold of 3 seconds (a number that was used during the testing of the compartment algorithm).

The detector polling algorithm must be invoked frequently to minimize the error in the stops, queue length (and therefore also delay) estimates. In other words, the IMP must be able to detect the switch from a compartment NON-QUEUED to a QUEUED state and vice versa, as quickly as

possible. During the validation of the compartment algorithm, the detector polling algorithm was invoked every 1/3 of a second.

The compartment algorithm is very sensitive to false detections. A false detection occurs when a detector turns ON even though no vehicle is present over the detector. Since the compartment algorithm is dependent on data accumulated over relatively long periods of time, errors in vehicle detections will tend to accumulate.

Another problem that can cause compartment algorithm snafus is due to lane changes. If a vehicle enters compartment 2 in lane 1 (figure 7) without first traveling through compartment 3, it will decrement the vehicle count in compartment 3, ultimately resulting in an inaccurate queue length estimate. Similarly, if a vehicle travels through compartment 3 in figure 7, and then changes lane without traveling through compartment 2, it will leave a 'residue' in compartment 2, thereby probably causing an inaccurate queue length estimate.

Overall, these problems point toward an inescapable fact. Over time, because of lane changes or false detections, the total number of vehicles in each compartment will slowly increase. To solve this problem, a two-step solution was developed. At the end of each time step, each compartment is checked. Two tests are performed. The first test is to check the vehicle count in each compartment. If it is greater than

the maximum number of vehicles that can possibly be in that compartment (assuming the compartments to be roughly evenly spaced along the lane and also assuming an average effective vehicle length of 22 feet), the vehicle count in that compartment is set to zero. Formally,

$$\text{If } (V_{i,j,t} * ACL > \frac{L_j}{N_j}) \text{ then } V_{i,j,t} = 0$$

where ACL is the average effective vehicle length, N_j is the number of compartments in lane j , L_j is the length of the roadway segment, and $V_{i,j,t}$ is the current vehicle count of compartment i in lane j . If the first test did not find any abnormalities, the second test is tried. The second test checks the time step volume of the compartment against the average volume of all the compartments in the lane during the last time step. If the volume in a compartment is 30% less than the average compartment lane volume and the average compartment volume is greater than 15 vehicles, the vehicle count in that compartment is set to zero. Formally,

$$\text{If } (V_{i,j,t} + 0.3 * \overline{V_{j,t}} < \overline{V_{j,t}}) \text{ and } (\overline{V_{j,t}} > 15) \text{ then } V_{i,j,t} = 0$$

where $\overline{V_{j,t}}$ is the average time step volume of lane j . This

second test attempts to correct for instances where an Autoscope detector becomes stuck ON.

6.2 INTERSECTION PRIMARY STOPS

In order to compute primary stops, the lane queue lengths at the current and previous time steps, as well as the vehicle arrivals and departures during the current time step are used. There are five different combinations of queue lengths and vehicle arrival/departure patterns that determine how the number of primary stops during each time step is calculated.

In the first case, the queue length recorded during the previous time step was zero, and the queue length at the current time step is greater than zero. In other words, if

$$Q_{j,t-1} = 0$$

$$Q_{j,t} > 0$$

Where $Q_{j,t-1}$ is the lane queue length recorded at the end of the previous time step and $Q_{j,t}$ is the lane queue length recorded at the end of the current time step. The total number of primary stops is then just the number of vehicles in the current queue, so

$$P_{j,t} = Q_{j,t}$$

In the second case of vehicle arrangements, the queue length at the end of the current time step is greater than the queue length recorded at the end of the previous time step, and the number of vehicles that left the roadway segment during the current time step is equal to zero. Formally, if

$$Q_{j,t} > Q_{j,t-1}$$

$$V_{j,t} = 0$$

where $V_{j,t}$ is the output volume from lane j during the current time step. This corresponds to a situation where no vehicles left the queue that formed during the previous time step, but vehicles joined at the end of the queue. The number of primary stops is then equal to the number of vehicles that joined the rear of the queue during the current time step, so

$$P_{j,t} = Q_{j,t} - Q_{j,t-1}$$

The vehicles originally in the queue will have been accounted for during a previous time step.

In the third case, the queue length recorded at the end of the current time step is equal to the queue length recorded at the end of the previous time step, and the number of vehicles that left the segment is equal to zero. Formally in case three,

$$Q_{j,t} = Q_{j,t-1}$$

$$V_{j,t} = 0$$

This means that during the current time step, no vehicles entered or left lane j of the roadway segment, so obviously the number of primary stops is equal to zero, or

$$P_{j,t} = 0$$

In the fourth case, the queue length recorded at the end of the previous time step was greater than zero, the number of vehicles that left the segment during the current time step was greater than zero, and the queue length recorded during the previous time step was greater than the number of vehicles that left the roadway segment during the current time

step. In other words,

$$V_{j,t} > 0$$

$$Q_{j,t-1} > 0$$

$$Q_{j,t-1} > V_{j,t}$$

The number of primary stops is then computed as

$$P_{j,t} = Q_{j,t} - (Q_{j,t-1} - V_{j,t})$$

which is equal to the number of vehicles that joined the queue during the current time step (the vehicles that were in the queue before the current time step will have been previously accounted for).

In the fifth and final case, the number of vehicles that left lane j of the roadway segment during the time step was greater than or equal to the number of vehicles in the queue at the end of the previous time step. Formally,

$$V_{j,t} \geq Q_{j,t-1}$$

This corresponds to a situation where all the vehicles in the queue from the previous time step had time to leave the roadway segment during the current time step. The number of primary stops for the current time step is then computed simply from the number of vehicles in the current queue, or

$$P_{j,t} = Q_{j,t}$$

Note that this algorithm must be invoked fairly frequently to function properly (it must be invoked at least once per cycle time of the intersection). If, between algorithm invocations, an existing queue disperses, and then a new queue forms and disperses, the number of stops by the

vehicles in the second queue will not be accounted for correctly.

6.3 TOTAL TRAVEL

6.3.1 INTERSECTION TT

At an intersection, the total travel algorithm uses very detailed detection information. Queue lengths recorded during the current and previous time steps, as well as vehicle input to and output from the roadway segment are used. It is also necessary to use an assumed average vehicle length in the calculations. Note that the concept of average vehicle length (ACL) also includes the average stopped space headway between vehicles, in addition to the length of the vehicle itself.

The TT estimation algorithm distinguishes between five cases of vehicle arrangements, that depend on the queue lengths and the arrival/departure patterns recorded during both the previous and the current time step.

In the first case, the queue length recorded at the end of the previous time step was zero, and the queue length at the current time step is greater than or equal to zero.

Formally,

$$Q_{j,t-1} = 0$$

$$Q_{j,t} > 0$$

In this case, the lane total travel becomes

$$TT_{j,t} = V_{j,t} * L_j + \sum_{i=0}^{Q_{j,t}-1} (L_j - i * ACL)$$

where $V_{j,t}$ is the total vehicle output from lane j during time step t , and L_j is the length in feet of the lane of the roadway segment being analyzed. L_j is allowed to vary from lane to lane, since the intersection may have a left turn bay or a right turn bay, or both, with different lengths than the through lane(s). $Q_{j,t}$ is the current lane queue length and ACL is the average vehicle length in feet (assumed to be 22 feet).

The first component of the equation measures the distance traveled within the intersection segment by the vehicles that traversed the entire segment. The second component of the equation measures the distance traveled by the vehicles that are in the current queue. These vehicles each traveled a distance less than or equal to the lane segment length. For instance, assuming a queue length of three vehicles and that the queue is formed at the stopline, the first vehicle in the queue traveled the whole segment length. The second vehicle in the queue traveled the whole segment length minus the length of the vehicle in front of it (or $L_j - ACL$). The third vehicle traveled the entire segment length minus the length of the two vehicles in front of it (or $L_j - 2ACL$), and so on, as given by the second component of the equation.

In the second case of vehicle arrival/departure patterns, the output volume, $V_{j,t}$ is equal to zero while the current lane queue length is greater than the queue length measured at the end of the previous time step. In more

concrete terms, this means that no vehicles left the segment during the current time step, but vehicles joined at the rear of the queue. The conditions are

$$V_{j,t} = 0$$

$$Q_{j,t} > Q_{j,t-1}$$

The total distance traveled by the vehicles that joined the queue is then given by

$$TT_{j,t} = \sum_{i=Q_{j,t-1}}^{Q_{j,t}-1} (L_j - i * ACL)$$

Where $Q_{j,t}$ is the current queue length estimate, and $Q_{j,t-1}$ is the queue length estimate recorded at the previous time step. The distance traveled by the vehicles that were already in the queue is obviously zero.

In the third case recognized by the TT algorithm, the output volume, $V_{j,t}$ is equal to zero while the current queue length is equal to the queue length measured during the previous time step. This means that during the last time step, no vehicles left the segment, and no vehicles arrived to join the end of the queue. Formally,

$$V_{j,t} = 0$$

$$Q_{j,t} = Q_{j,t-1}$$

Consequently, total travel for the time step is zero.

In the fourth case, $V_{j,t}$ is greater than zero, the queue length measured during the previous interval was greater than zero, and the previously measured queue length is greater than

$V_{j,t}$. This corresponds to a situation where not all of the vehicles originally in the queue had time to clear the intersection during the last time step. Formally then,

$$\begin{aligned} V_{j,t} &> 0 \\ Q_{j,t-1} &> 0 \\ Q_{j,t-1} &> V_{j,t} \end{aligned}$$

Total travel is then calculated as

$$TT_{j,t} = \sum_{i=0}^{V_{j,t}-1} (i \cdot ACL) + (Q_{j,t-1} - V_{j,t}) \cdot ACL \cdot V_{j,t} + \sum_{i=Q_{j,t-1}-V_{j,t}}^{Q_{j,t}-1} (L_j - i \cdot ACL)$$

The first term in the equation measures the distance traveled by those vehicles originally in the queue that had time to clear the intersection during the time step. The second term measures the distance traveled by those vehicles that were initially in the queue and did not have time to clear the intersection. The third term measures the distance traveled by those vehicles that joined the tail of the queue during the time step (they did obviously not have time to clear the intersection). An example of how this somewhat elaborate formulation works is shown in figure 10. Here, the initial queue length is five vehicles, with their front bumpers separated by one average vehicle length, or ACL. During the time step, two vehicles clear the intersection, so $V_{j,t} = 2$. The distance traveled by the first vehicle in the original queue is 0, and the distance traveled by the second vehicle is

Note that the total travel algorithm does depend on data accumulated over time (i.e., the algorithm depends on the data from the current time step as well as the previous time step, which in turn depends on the data from the time step before that, etc). If no data error checking and correction facility was available, errors in vehicle detections would tend to accumulate, and distort the travel time estimates. Fortunately, since the algorithm depends on queue lengths (which are checked for errors as explained in section 6.1), and vehicle inputs to and output from the system (data which is given only for the current time step), the algorithm will not accumulate vehicle detection errors over time. As is the case with the stops algorithm, this algorithm should be invoked at least once per intersection cycle time. The time step should be no longer than the intersection cycle length; a time step of 1/4 to 1/2 the cycle length is ideal for 'catching' the behavior of most queues in sufficient detail.

6.3.2 HIGHWAY TT

At a highway segment, the total travel per lane per time step is calculated from the average time step lane volume, which is given by

$$\overline{V}_{j,t} = \frac{\sum_{d=1}^N V_{d,j,t}}{N}$$

where N is the number of detectors in lane j. Total travel per lane over time step t is then

the length of the vehicle in front of it plus the stopped space headway, or ACL, as described by the first term in the equation. The three vehicles that never cleared the intersection (but were in the original queue) each traveled a distance equal to the length of all the vehicles in front of them that cleared the intersection, or

$$V_{j,t} * ACL$$

There were

$$Q_{j,t-1} - V_{j,t}$$

vehicles that traveled this distance, so the total distance traveled is obtained by multiplying the two expressions, as given by term two. The vehicles that joined the tail of the queue during the interval (such as vehicle 6 in figure 10) each traveled the segment length minus the length of all the vehicles in front of them in the current queue, as expressed by the third term in the equation.

The fifth and final case of total travel estimates occurs when $V_{j,t}$ is greater than or equal to $Q_{j,t-1}$, which corresponds to a situation where all vehicles in the queue from the previous time step had time to clear the intersection, and newly arrived vehicles are forming a new queue. In this case, total travel is given by

$$TT_{j,t} = \sum_{i=0}^{Q_{j,t-1}-1} (i * ACL) + (V_{j,t} - Q_{j,t-1}) * L_j + \sum_{i=0}^{Q_{j,t}-1} (L_j - i * ACL)$$

$$TT_{j,t} = \overline{V_{j,t}} * L$$

where L is the length in feet of the roadway segment being analyzed, (which is assumed not to vary lane-by-lane). This equation might seem somewhat simplistic compared to the rather elaborate formulation used for intersections. Keep in mind, however, that volumes at highway segments are considerably higher than volumes at intersections (by at least 2:1), so that each individual vehicle at a highway segment in a sense becomes 'less important' for the time step travel time estimate (unless each time step is very short).

Lane changes is a source of possible errors. For the purposes of this report, the errors caused by lane changes were considered irrelevant.

6.4 TOTAL TRAVEL TIME

6.4.1 INTERSECTION TTT

Total travel time in each lane of an intersection is approximated by the following equation

$$TTT_{j,t} = D_{j,t} + \frac{TT_{j,t}}{S}$$

The first term, $D_{j,t}$, measures the total stopped delay during the time step, which is derived by numerically integrating the area under the queue length versus time curve (as shown in figure 1 and explained in section 6.1).

The second term in the equation measures travel time in addition to the stopped time. This term assumes an average

travel speed, S , for a vehicle traveling, without stopping, through the intersection (S is a user-defined parameter, see Appendix A) - i.e., given the total distance traveled, how long would it take a vehicle to travel that distance if it traveled at what is perceived by the user to be the average travel speed. Note that this equation does not take into account additional travel times due to vehicle acceleration and deceleration.

6.4.2 HIGHWAY TTT

At a highway segment, the following relationship is used [1], [4]:

$$TTT_{j,t} = \frac{TT_{j,t}}{S_{j,t}}$$

where $S_{j,t}$ is the space mean speed in lane j , $TT_{j,t}$ is the total travel in lane j , and $TTT_{j,t}$ is the total travel time in lane j , during the last time step. $TT_{j,t}$ and $S_{j,t}$ are known (as explained in sections 6.3.2 and 6.5), so $TTT_{j,t}$ can be obtained.

6.5 HIGHWAY DELAY MEASUREMENTS

A delay measure at a highway segment can be extracted quite simply from vehicle counts and average speeds by determining the total travel time of all vehicles that traveled through the roadway segment being analyzed, and then subtracting from that the 'ideal' total travel time. The difference can be interpreted as delay [1], [4]. The actual

lane TTT per time step is given by

$$TTT_{j,t} = \frac{\overline{V}_{j,t} * L}{S_{j,t}} = \frac{TT_{j,t}}{S_{j,t}}$$

where L is the length of the roadway segment, $S_{j,t}$ is the lane space mean speed, and $\overline{V}_{j,t}$ is the average lane volume, as

derived in section 6.3.2. $S_{j,t}$ is obtained by computing the space mean speed of each speed trap in each lane, and then averaging those values to obtain the lane space mean speed. Formally,

$$S_{j,t} = \frac{\sum_{d=1}^N S_{d,j,t}}{N}$$

where N denotes the number of detectors in lane j. The space mean speed $S_{d,j,t}$ of detector d in lane j is obtained by computing the harmonic mean of the (point-measured) speeds of all vehicles that passed through the section of roadway during time step t.

This actual travel time can be compared to an 'ideal' travel time obtained during 'ideal' travel conditions. Ideal travel conditions are defined to include (among other things) uninterrupted flow, a traffic stream consisting of exclusively passenger cars, and 12 foot lane widths. Therefore, the ideal travel time for the same number of vehicles is given by

$$TTT_{j,t,IDEAL} = \frac{\overline{V}_{j,t} * L}{S_{IDEAL}} = \frac{TT_{j,t}}{S_{IDEAL}}$$

where $TTT_{j,t,IDEAL}$ is the ideal travel time for lane j , and S_{IDEAL} is the ideal speed of a vehicle using the highway, often defined as the design speed of the highway. The highway design speed is a parameter to the IMP program, entered by the user. It defaults to 60 mph (see Appendix A). The time step total delay, $D_{j,t}$ (so-called travel time delay) [4], is then given by

$$D_{j,t} = TTT_{j,t} - TTT_{j,t,IDEAL}$$

6.6 FUEL CONSUMPTION

Many fuel consumption algorithms rely on very detailed data such as detailed time-space trajectories of individual vehicles, or instantaneous rates of fuel consumption of each vehicle [9]. In most cases the Traffic Engineer does not have access to such information.

For the purposes of this report, rather than using fuel consumption algorithms that rely on individual vehicle characteristics, emphasis was placed on finding reasonably recent algorithms that use parameters that can be easily obtained and accurately measured, such as speeds, travel times and distance traveled. The algorithms rely extensively on constants that have been obtained by fitting collected vehicle data to mathematical models using statistical methods, a 'necessary evil' since the algorithms do not rely on individual vehicle information. Rather, the algorithms rely on

the fuel consumed by the average vehicle in the traffic stream [9]. The algorithms were developed so recently however, that the constants they rely on give a reasonable representation of the fuel consumption of the current vehicle fleet.

All the highway fuel consumption and vehicle emissions equations are taken from a study undertaken by the Federal Highway Administration [9]. In this study, one-second speed and acceleration data from the Long Island Expressway was used. The study also made use of detailed fuel consumption and vehicle emissions rates from 15 vehicles that are expected to "represent 64 percent of the 1980-1992 vehicle population". From this data, plots showing fuel consumption and vehicle emission rates for various speeds were produced. Then, the vehicles in the current vehicle fleet were matched with one of the 15 test vehicles, in terms of number of cylinders, engine displacement etc. Since it is known approximately how large a share of the vehicle fleet each of the 15 test vehicles represent, fuel consumption and vehicle emissions of the 'average' vehicle in the vehicle fleet could be calculated. Then, statistical methods were used to "determine the most appropriate relationships between fuel consumption and vehicle emissions and various descriptive parameters". Note that none of the fuel consumption and vehicle emissions equations used at highways account for large vehicles like tractor trailers (light trucks are included). The equations are presented in sections 6.6.1 - 6.7.3.2.

6.6.1 INTERSECTION FUEL CONSUMPTION

The intersection fuel consumption model (from [5]) is expressed as

$$FC_{j,t} = F1 * TT_{j,t} + F2 * D_{j,t} + F3 * P_{j,t}$$

where $FC_{j,t}$ is the fuel consumption in gallons, $TT_{j,t}$ is the total distance traveled in vehicle miles, $D_{j,t}$ is the total stopped delay in vehicle hours, and $P_{j,t}$ is the number of primary stops. $F1$, $F2$ and $F3$ in turn are related to the average speed at the intersection, with

$$F1 = 0.071137 + \frac{2.14}{S_{j,t}} + 0.000039 * S_{j,t}$$

$$F2 = 2.14$$

$$F3 = 10^{-3} * (2.113 \times 10^{-1} * S_{(j,t)} + 1.38 \times 10^{-2} * S_{(j,t)}^2 + 2 \times 10^{-6} * S_{(j,t)}^4)$$

where $S_{j,t}$ is the lane space mean speed, given by $TT_{j,t}/TTT_{j,t}$ [16]. $F1$ is calculating the fuel consumption per unit distance while cruising, $F2$ gives the fuel consumption per unit time while idling, and $F3$ gives the fuel consumption per primary stop.

The equation calculating fuel consumption is of a so-called elemental form, similar to the equation developed by Akcelik [18]. Elemental models are "suitable for macro transport or urban form analyses" [19], because they are simple to use, reasonably accurate and because the input data is relatively easy to collect. Elemental models also have an

advantage over 'straight' regression models, in that the "individual predictor variables are independent" [18]. Therefore the coefficients F1, F2 and F3 are determined separately (F1, the fuel consumption per unit distance is determined independently of the fuel consumption per unit time, F2, and so on). Hence, the elemental models are responsive to changes in the predictor variables (in this case TT, D and P) whereas 'straight' regression models are not, or at least responsive to a lesser degree.

6.6.2 HIGHWAY FUEL CONSUMPTION

At a highway segment, the algorithm (taken from [9]), is given by

$$FC_{j,t} = \frac{F1 * TT_{j,t}}{1000} + \frac{F2 * TTT_{j,t}}{1000}$$

where $FC_{j,t}$ is the fuel consumption in gallons, $TT_{j,t}$ is the total distance traveled in vehicle-feet, and $TTT_{j,t}$ is the total travel time in vehicle-seconds. F1 is a constant representing the fuel consumed per unit distance (F1 equals 0.00657), while F2 is a constant related to various time-dependent losses, mainly idling fuel consumption (F2 equals 0.20319).

6.7 VEHICLE EMISSIONS

As is the case with fuel consumption, vehicle emissions depend on the characteristics of each individual vehicle, such as the size and type of the engine, the presence or absence of catalytic converters and the driving behavior of each

individual. Many emissions calculation algorithms that rely on the behavior of each individual vehicle have been developed [9]. For the purposes of this project those algorithms were disregarded, since the data they require is usually not available to the Traffic Engineer. Instead, the project focused on finding algorithms that rely on common parameters that can be easily measured over time, such as speeds, travel times and travel distances. While in some cases relying on statistical fitting of mathematical models, and therefore the emissions of an average vehicle, most of the algorithms were developed so recently that they give a reasonably accurate representation of vehicle emissions of the current vehicle fleet. For a discussion of the highway emissions equations, see section 6.6.

6.7.1 NITROUS OXIDE EMISSIONS

6.7.1.1 INTERSECTION NOX EMISSIONS

The intersection nitrous oxide emissions equation that IMP uses is very simple,

$$NOX_{j,t} = 2 + 0.043 * S_{j,t}$$

where $NOX_{j,t}$ is the amount of Nitrous oxides emitted in grams, and $S_{j,t}$ is the lane space mean speed approximated by $TT_{j,t}/TTT_{j,t}$. This equation relies on the near-linear relationship between speeds and vehicle NOX emissions as reported by [17]. This algorithm is the least recent of the MOE algorithms presented in this paper; it uses vehicle emissions data from 1975 and will therefore overestimate the

amount of NOX emissions. Unfortunately this was the only acceptable algorithm found in the literature review.

6.7.1.2 HIGHWAY NOX EMISSIONS

At a highway segment (from [9]),

$$NOX_{j,t} = \frac{126.504 * TT_{j,t}}{1000} + \frac{493.108 * TTT_{j,t}}{1000}$$

where $NOX_{j,t}$ is the amount of nitrous oxides emitted in milligrams, $TT_{j,t}$ is the total distance traveled in feet, and $TTT_{j,t}$ is the total travel time in seconds. IMP internally converts NOX to grams.

6.7.2 CARBON MONOXIDE (CO) EMISSIONS

6.7.2.1 INTERSECTION CO EMISSIONS

At an intersection, the amount of CO emissions in grams per kilometer is given by

$$CO_{j,t} = 171.71 - 23.87 * S_{j,t} + 0.096 * S_{(j,t)}^2$$

where $S_{j,t}$ is the lane space mean speed in kilometers per hour. The IMP program internally converts the speeds to kilometers per hour and the CO output value to grams. This model relies on the strong correlation between average speed and CO emissions found by [16]. This study used the microscopic network simulation program NETSIM to get detailed speed data. From the data, emissions were determined from vehicle emissions tables. Then, a regression analysis was performed to determine the relationship between vehicle emissions and average speed. The result was the equation used here, and the

equation used for intersection HC emissions (see section 6.7.3.1). Note that this model was tested with average travel speeds no higher than 30 km/h (about 19 mph). Trucks and other heavy vehicles were not included in the vehicle population.

6.7.2.2 HIGHWAY CO EMISSIONS

At a highway segment, CO emissions in milligrams (from [9]) is given by

$$CO_{j,t} = \frac{1689.647 * TT_{j,t}}{1000} + \frac{-29338.968 * TTT_{j,t}}{1000}$$

where $TT_{j,t}$ is the total distance traveled in vehicle feet, and $TTT_{j,t}$ is the total travel time in vehicle seconds, as given in sections 6.3.2 and 6.4.2. IMP internally converts $CO_{j,t}$ to grams.

6.7.3 HYDROCARBON (HC) EMISSIONS

6.7.3.1 INTERSECTION HC EMISSIONS

At an intersection the amount of HC emissions in milligrams is given by

$$HC_{j,t} = 8.342 - 1.065 * S_{j,t} + 0.0483 * S_{(j,t)}^2$$

where $S_{j,t}$ is the space mean speed, approximated by $TT_{j,t}/TTT_{j,t}$. IMP internally converts $HC_{j,t}$ to grams. This model relies on the strong correlation between HC emissions and average travel speed reported by [16]. For a discussion of this study, see section 6.7.2.1. Note that this model was only tested using average speeds of up to 30 km/h (about 19 mph).

6.7.3.2 HIGHWAY HC EMISSIONS

At a highway segment (from [9]), the amount of hydrocarbons emitted per time step (in milligrams) is given by

$$HC_{j,t} = \frac{21.886 * TT_{j,t}}{1000} + \frac{454.409 * TTT_{j,t}}{1000}$$

where $TT_{j,t}$ is the total distance traveled in vehicle-feet and $TTT_{j,t}$ the total travel time in vehicle-seconds. IMP converts $HC_{j,t}$ to grams.

6.8 LEVEL OF SERVICE

6.8.1 INTERSECTION LOS

To calculate intersection LOS, the criteria of average vehicle stopped delay given in figure 2 are used [8]. The average stopped delay is computed by dividing the total lane time step delay (as derived in section 6.1) with the lane time step output volume, as measured by the lane stopline detector, plus the number of vehicles in the current queue. Formally,

$$\overline{D_{j,t}} = \frac{D_{j,t}}{V_{j,t} + Q_{j,t}}$$

6.8.2 HIGHWAY LOS

At a highway segment, the IMP uses the density information from figure 3 to compute Level of Service (from criteria developed by [8]). The IMP has an input parameter that lets the user enter the percentage of heavy vehicles in the traffic stream. The time step volume measures are then converted to passenger car equivalents using the heavy vehicle

percentage (see Appendix A).

The density is approximated by using the familiar

$$k_{j,t} = q_{j,t}/S_{j,t}$$

where $q_{j,t}$ is the flow (in passenger cars per hour), $S_{j,t}$ is the space mean speed (in miles per hour) and $k_{j,t}$ is the density (in passenger cars per mile) [7].

7. TESTING AND VERIFICATION

In the following section, MOE testing results are presented. It should be mentioned that the version of Autoscope used during the testing process was a test version, and not the final product. The final product is expected to have a higher detection accuracy. Also, the camera placements at the test sites cannot be considered ideal; as mentioned previously the cameras were placed at the side of the road instead of at the center (except the 26th St camera); at the intersection test site, a higher camera placement would probably increase the Autoscope detection accuracy.

Unfortunately, the fuel consumption and emissions data could not be directly verified. However, the input parameters to the fuel consumption and emissions models (stops, TT, TTT etc) were manually verified.

7.1 INTERSECTION MOE TESTING AND VALIDATION

At the intersection test site, IMP data acquired from the leftmost lane of travel was compared to manual data. The intersection detector layout is shown in figure 4. Detector 0 was placed approximately 70 ground feet from the camera.

Detectors 1, 2 and 3 were placed with even spacing along the approach, approximately 185, 300 and 415 ground feet from the camera, respectively. Two test tapes were used. The first test tape was recorded from 11:40 to 13:40 PM on a weekday, with little to moderate congestion. The second test tape was recorded from 16:45 to 18:45 PM on a weekday, with moderate congestion. MOE data from the first hour from both tapes was collected and manually verified.

To determine the volume accuracy of the Autoscope detectors, manual volume counts (including lane changes) were compared to Autoscope counts. The one-hour volume comparisons of the intersection tapes are shown in tables 1 and 2.

TABLE 1 - Autoscope Volume Accuracy, Intersection Tape 1				
Detector No.	Manual Count	Autoscope Count	Err	Err (%)
Detector 0	520	498	-22	-4.2
Detector 1	521	469	-52	-10.0
Detector 2	525	414	-111	-21.1
Detector 3	534	386	-148	-27.7

TABLE 2 - Autoscope Volume Accuracy, Intersection Tape 2				
Detector No.	Manual Count	Autoscope Count	Err	Err (%)
Detector 0	791	804	11	1.3
Detector 1	790	725	-65	-7.6
Detector 2	787	730	-57	-7.2
Detector 3	797	662	-135	-16.9

The detectors placed close to the camera performed very well. As the distance between detectors and the camera increased however, Autoscope volume accuracy began to suffer, due to low vehicle separation on the video image. The Autoscope volume accuracy was higher on tape 2, even though this tape exhibited a higher degree of congestion. This was most likely due to more favorable light conditions, which made it easier to detect individual vehicles within platoons.

Queue length accuracy was tested by manually sampling the queue length every 15 seconds, and comparing this with the IMP queue length estimate. Similarly, primary stops were computed manually by summing the number of primary stops every 15 seconds. Delay was computed manually by integrating the queue length vs time curve (using the 15-second manual queue length counts), and comparing this with the IMP delay

estimate.

Plots comparing manual and IMP queue length and stop counts from tapes 1 and 2 are shown in figures 11 - 14. The plots show one-minute samples of the (15-second) queue lengths and stops, to give a better indication of IMP performance over a long period of time. The graphs can be summarized as in tables 3 and 4.

TABLE 3 - Comparison of Intersection Tape 1 Stops, Queue Lengths and Delay				
	Manual	IMP	Err	Err (%)
Total Queued Vehicles	130	113	-17	-13.1
Total Delay (veh-hrs)	2.03	1.87	-0.16	-7.9
Total Stops	70	60	-10	-14.3

TABLE 4 - Comparison of Intersection Tape 2 Stops, Queue Lengths and Delay				
	Manual	IMP	Err	Err (%)
Total Queued Vehicles	154	120	-34	-22.1
Total Delay (veh-hrs)	2.52	1.98	-0.54	-21.4
Total Stops	78	68	-10	-12.8

It is evident that the IMP was consistently

underestimating the queue lengths and stops. This was to be expected, and was to a large extent due to low-speed platoon arrivals, where the Autoscope detectors failed to pick up individual vehicles within the platoon.

The average difference between the manual and IMP queue counts was -0.27 on tape 1 and -0.54 on tape 2. In other words, at any time step the IMP was likely to underestimate the true queue length by a quarter of a vehicle on tape 1, and by approximately half a vehicle on tape 2. The average difference between the manual and IMP stop counts was -0.16 on both tapes.

Lane changes were not very frequent (tape 1 had 22 lane changes that affected IMP performance, about 4 percent of the total number of vehicles; tape 2 had similar numbers) and did not seem to have any great effect on queue length or stop estimates.

In some instances, the IMP was underestimating the queue length or stops in one 15-second time step, only to give the correct estimate in the next 15-second time step. This was probably due to a compartment not being considered QUEUED during the first time step, and being considered QUEUED in the next (i.e., during the first time step, the vehicle had not been stationed over the detector long enough to put the detector's compartment in a QUEUED state).

IMP travel times and total travel were compared against 5-minute manual estimates. Total travel for each 5-minute

period was computed manually by multiplying the 5-minute output volume by the length of the roadway segment (350 feet), and adding the approximate distance traveled by the vehicles 'stored' within the intersection at the end of the time step.

Average travel times were obtained by sampling the vehicle density within the roadway section every 15 seconds, for 5 minutes. Average travel time (in seconds) per 5-minute time step can then be computed as

$$\overline{T_{j,t}} = \frac{N_{j,t} T_s}{V_{j,t}}$$

where $\overline{T_{j,t}}$ is the time step average travel time, $N_{j,t}$ is the sum of the 15-second density counts, T_s is the sampling time step (15 seconds), and $V_{j,t}$ is the 5-minute output volume [6]. From this value, total travel time can be computed by simply multiplying $\overline{T_{j,t}}$ by $V_{j,t}$. The TT and TTT comparisons are displayed in figures 15 - 18. The data is summarized in tables 5 and 6.

TABLE 5 - Comparison of Intersection Tape 1				
TT, TTT				
	Manual	IMP	Err	Err (%)
Total TT (veh-mi)	36.3	33.1	-3.2	-8.8
Total TTT (veh-hrs)	3.43	3.74	0.31	9.0

TABLE 6 - Comparison of Intersection Tape 2				
TT, TTT				
	Manual	IMP	Err	Err (%)
Total TT (veh-mi)	52.7	52.5	-0.2	-0.4
Total TTT (veh-hrs)	4.05	4.91	0.86	21.2

IMP was overestimating total travel time, most likely because the average travel speed for non-stopping vehicles was assumed to be 20 mph, which is somewhat low. The 20 mph average travel speed was obtained by manually recording travel times of 10 non-stopping vehicles, and dividing the length of the roadway segment by the average of the recorded travel times.

Table 7 shows the cumulative fuel consumption, emissions and average LOS for the two intersection tapes, as computed by IMP. Average LOS was computed by assigning each 15-second LOS estimate to a number (A=5, B=4, etc.) and

determining the average LOS from the arithmetic mean of the 'numerical' LOS measures.

TABLE 7 - Intersection Other MOE's		
	Tape 1	Tape 2
Fuel Consumption (gallons)	15.75	20.6
HC Emissions (grams)	105.3	280.9
CO Emissions (grams)	202.1	300.7
NOX Emissions (grams)	5.82	9.89
Average LOS	B	B

7.2 HIGHWAY MOE TESTING AND VALIDATION

At the highway test sites, the IMP algorithms were tested using manual counts and manually computed MOE estimates. The testing was performed using two one-hour tape sequences from the test sites.

7.2.1 26TH ST TAPE

First, volume, speed and MOE data from lane 1 at the 26th Street test site was verified using manual methods. The 26th Street tape was recorded from 8 AM to 9 AM on a weekday and showed traffic conditions with moderate to heavy congestion. The detector layout is shown in figure 5. The distance from the camera to detector 4 (the detector closest to the camera) was about 150 ground feet. The distance from

the camera to detector 0 was approximately 390 ground feet. A 5-minute time step was used. First, the detection ratio of each detector over time was determined. Detection ratio was determined using the following formula :

$$DR_{d,t} = \frac{V_{d,t,AUTOSCOPE} - V_{d,t,MANUAL}}{V_{d,t,MANUAL}} * 100 + 100$$

where $DR_{d,t}$ is the detection ratio of detector d at time step t, $V_{d,t,AUTOSCOPE}$ is the Autoscope time step volume count, and $V_{d,t,MANUAL}$ is the manual time step volume count. A detection ratio below 100 indicates that the Autoscope is undercounting; if the detection ratio is above 100, the Autoscope is overcounting. Specifically, a detection ratio of 97 would indicate that the Autoscope is failing to count 3% of the vehicles; similarly a detection ratio of 103 would indicate that the Autoscope is overcounting by 3%.

The detection ratios for detectors 0 and 4 at the 26th St test site are shown in figure 19. The volume counts are summed in table 8 (for detailed data see Appendix B, which also shows results from lane 2).

TABLE 8 - Autoscope Volume Accuracy, 26th St Tape				
Detector No.	Manual Count	Autoscope Count	Err	Err (%)
Detector 0	1877	1882	5	0.3
Detector 4	1882	1519	-363	-19.3

The detector close to the camera performed almost flawlessly. At a distance, vehicle separation was very low, which accounts for the decreased performance of detector 4.

IMP space mean speeds, total travel and total travel times were also compared with manual estimates. To manually determine space mean speeds, 10 sample travel times were recorded during each 5-minute time step using a stop watch. The length of the highway segment divided by the average of the travel times was taken to represent the space mean speed [4].

Total travel was computed by taking the average of the manual input and output volume counts in the lane and multiplying that number by the length of the roadway segment.

Delay was derived manually by computing $TT_{j,t}$ as $TT_{j,t}/S_{j,t}$, and subtracting the time step ideal total travel time $TT_{j,t}/S_{IDEAL}$ (as described in section 6.5). The comparison results are shown in figures 20 - 22. The MOE data is summarized in tables 9 and 10 (table 10 shows the IMP fuel

consumption and emissions calculations).

TABLE 9 - Comparison of Highway MOE's - 26th St Lane 1				
	Manual	IMP	Err	Err (%)
Avg Space Mean Speed	33.6	33.8	0.2	0.6
Total Travel (veh-miles)	85.43	78.14	-7.29	-8.5
Delay (veh-hrs)	1.47	1.25	-0.22	-15.0

TABLE 10 - 26th St Other MOE's	
	Lane 1
Fuel Consumption (gallons)	4.47
HC Emissions (grams)	12.93
CO Emissions (grams)	414.4
NOX Emissions (grams)	55.4
Average LOS	E

IMP underestimated total travel and delay, which was to be expected, since those estimates are directly linked to the Autoscope volume accuracy. As figure 19 shows, the Autoscope detector located 390 ground feet from the camera, was consistently undercounting. Average LOS was computed as explained in section 7.1.

7.2.2 LYNDALE AVE TAPE

This tape was recorded during morning rush hour (7:10 - 8:10 AM) on a weekday. Data from lane 2 was tested against manually computed data, using a 5-minute time step (detailed data for lanes 2 and 3 is shown in Appendix B). Figure 6 shows the Lyndale detector layout. Detector 1 (the detector closest to the camera) was placed approximately 150 ground feet from the camera. Detector 4 was placed approximately 330 ground feet from the camera. The Lyndale tape had heavy congestion and fluctuating driving conditions. During one 5-minute time step, the traffic could be stopped for several minutes; during other time steps, the traffic could be moving at 35-40 mph.

The detection ratio data is shown in figure 23; the volume counts are summarized in table 11.

TABLE 11 - Autoscope Volume Accuracy, Lyndale Tape				
Detector No.	Manual Count	Autoscope Count	Err	Err (%)
Detector 1	1949	2024	75	3.8
Detector 4	1917	1777	-140	-7.3

Again, Autoscope performed very well at the detector location close to the camera, while having some problems at a distance. However, the far detector performed much better compared with the 26th Street far detector, because of a more

favorable camera angle, and because it was placed closer to the camera. The light conditions were also more favorable. The sun was rising and shining directly at the front bumper of each vehicle, making the transition between closely spaced vehicles clearly defined, even though the space headways were small. In some cases, a vehicle would be counted twice, once when the front bumper triggered the detector, and once when the windshield triggered the detector.

The MOE data is shown in figures 24 - 26 and summarized in tables 12 and 13.

TABLE 12 - Comparison of Highway MOE's - Lyndale Lane 2				
	Manual	IMP	Err	Err (%)
Avg Space Mean Speed	22.0	21.0	-1.0	-4.5
Total Travel (veh-miles)	65.9	70.3	4.37	6.6
Delay (veh-hrs)	2.06	2.21	0.15	7.3

TABLE 13 - Lyndale Ave Other MOE's	
	Lane 2
Fuel Consumption (gallons)	4.42
HC Emissions (grams)	12.3
CO Emissions (grams)	245.4

TABLE 13 - Lyndale Ave Other MOE's	
	Lane 2
NOX Emissions (grams)	47.77
Average LOS	F

The space mean speeds were difficult to determine manually, since the range of speeds within each 5-minute time step was likely to be large (vehicles could be traveling at anywhere from 3-5 mph to over 35 mph). However, the Autoscope space mean speed curve shown in figure 24 is essentially a damped version of the manually derived space mean speed curve. Predictably, IMP was overestimating delays and total travel, since the Autoscope detectors were overcounting slightly. It is of some concern that the emissions estimates (especially the CO estimates) were low as compared with the 26th St tape. This seems counter intuitive, since the Lyndale Ave tape was actually more congested.

8. CONCLUSIONS

A method for automatically estimating many critical MOE's at intersections and highway segments utilizing the Autoscope image processing vehicle detection technology has been presented. A program (called IMP), running under the Windows operating system has been developed. IMP has the capability to derive the most commonly used MOE's by analyzing

the Autoscope vehicle detection data in real time. The MOE data can then be displayed numerically or graphically, and/or be saved to a data file. While the test results given in this paper by no means represent an exhaustive test of the proposed MOE estimation algorithms, it can preliminarily be concluded that the algorithms perform reasonably well.

Unfortunately, the fuel consumption and emissions estimates could not be tested directly, due to a lack of reliable comparison data. However, the data used as input parameters to the fuel consumption and emissions algorithms (primary stops, TT, TTT etc) were manually tested, and exhibited satisfactory performance.

Note that all of the MOE algorithms are directly dependent on the Autoscope detection accuracy. The testing was performed almost exclusively during adverse traffic flow conditions, which is when the Traffic Engineer is most likely to desire access to accurate MOE data. Autoscope detectors located less than 350 ground feet from the camera were very accurate. However, the high congestion negatively affected detection accuracy at detector locations more than 350 ground feet from the camera (the low vehicle separation caused the Autoscope to detect platoons rather than individual vehicles). The IMP MOE estimates were reasonably accurate, in spite of the (sometimes) low volume accuracy of the Autoscope detectors. IMP MOE estimates obtained during light flow conditions are likely to be even more accurate, since the

Autoscope detection accuracy will then presumably be higher.

In summary, it can be concluded that the Autoscope-Supervisor-IMP combination presents an attractive solution to the problem of real time traffic parameter and MOE data collection at intersections and highway segments, because of the accuracy of the MOE estimates and because the data collection process is essentially fully automated.

9. SUGGESTIONS FOR FURTHER RESEARCH

Further research on the MOE algorithms presented in this paper is suggested. First, the MOE algorithms (especially the fuel consumption and emissions algorithms) need to be validated at additional roadway segments (both intersections and highway segments) with varying road geometry and flow conditions. Second, the method for manually determining the QUEUED threshold for the stopline detector at an intersection needs to be further researched and formalized (the QUEUED threshold is used to determine when to put a compartment in a QUEUED state). Third, a more accurate method for automatically determining the QUEUED threshold for each detector (given the manual QUEUED threshold of the stopline detector) is also desired. Because of the perspective view of the camera, detectors will 'cover' proportionally more road surface per screen pixel as the real-world distance from the camera increases, therefore the QUEUED threshold of detectors of equal size will vary depending on the real-world distance from the camera to the detectors.

10. REFERENCES

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11. APPENDIX A. IMP PARAMETERS

The following IMP parameters must be specified by the user at each test site (they are IMP menu options) and can then be saved in a configuration file for later quick recall.

Number of Lanes The number of lanes at the current test site.

Number of Detectors The number of detectors at the current test site.

Lane/Detector Configuration This parameter enables the user to register with the IMP which detectors are in which lane, and the ordering of detectors in that lane (for example the user can specify that detector 14 is the third detector from the stopline in the lane 1). This is very important, since it forms the very basis of the detector polling algorithm, which enables the IMP to determine when queues are forming, etc.

StopThreshold This parameter specifies how long a detector must be ON before its associated compartment goes into a QUEUED state (possible values 1,2,3,4 and 5 seconds). Because of the perspective view of the camera (assuming that the camera is located at the stopline and facing the intersection approach), a vehicle passing over a call detector in 3 seconds, will pass over the stopline detector in perhaps only 1 to 2 seconds. In other words, as detectors are placed farther away from the camera, they will 'cover' more space on the roadway and therefore vehicles will leave the detectors ON for longer amounts of time. To adjust for that fact, the IMP assumes that the StopThreshold is given for the stopline detector, and only allows queues to form starting at the stopline.

TimeSlice Specifies the duration of a time step - i.e., how often IMP should save real-time data to an IMP data file (possible values 15 sec, 30 sec, 1, 5, 10, 15 and 60 minutes). Every TimeSlice interval, IMP will add the MOE's for each lane and write this data to a file for later analysis.

PollSlice Specifies how often the IMP polling algorithm should

poll all the detectors to determine the state of their compartments (possible values 1,2,3,4,5 times per second). This parameter is effectively used only at intersection test sites.

SegmentLength At both an intersection and a highway camera location, this parameter represents the real world distance from the upstream to the downstream boundary of the roadway segment - the length of the roadway segment being analyzed. At an intersection test site three values can be entered here, one describing the distance from the stopline to the right turn call detector (or the beginning of the right turn bay), one describing the distance from the stopline to the through lane call detector, and one describing the distance from the stopline to the left turn call detector (or the beginning of the left turn bay). The maximum allowed value for this parameter at an intersection is 400 feet.

At a highway location, this parameter also describes the length of the roadway segment being analyzed. Only one value is allowed and will be used for all lanes.

Design Speed At a highway location, this parameter enables the user to enter the highway design speed at the camera location (choices are 50, 60 and 70 mph with 60 mph being the default). This value is used to compute highway delay and highway level of service.

At an intersection location, this parameter specifies the average perceived travel speed of non-stopping vehicles at the intersection (choices are 25, 30 or 35 mph); this parameter is used to estimate intersection total travel time.

Heavy Vehicles Enables the user to enter the percentage of heavy vehicles in the traffic stream (where heavy vehicles include trucks, buses and recreational vehicles). At a highway test site, this measure is used to translate the time step volumes to an equivalent number of passenger cars. IMP simply takes the number of heavy vehicles and multiplies it by a factor of 1.5, to arrive at the number of passenger cars. This

measure (1.5) is derived from the Highway Capacity Manual table (3-3), by simply averaging the passenger car equivalence multipliers given for buses, trucks and heavy vehicles. The default percentage of heavy vehicles is 10. This parameter is ignored at an intersection location.

12. APPENDIX B. TEST DATA

Queue length study from tape 4/7/91 11:40-1:40 (Tape 1)
 15 second QUEUE LENGTH Counts, sampled every minute

Time (min)	Manual Count	IMP Count	Diff erence	Time (min)	Manual Count	IMP Count	Diff erence
1	0	0	0	35	0	0	0
	2	2	0		0	0	0
	0	0	0		2	0	-2
	0	0	0		0	0	0
5	0	0	0	40	3	3	0
	0	0	0		0	0	0
	2	2	0		13	5	-6
	1	0	-1		4	2	-2
	3	4	1		11	8	-3
10	1	1	0	45	0	0	0
	0	0	0		1	0	-1
	3	2	-1		0	0	0
	4	4	0		4	2	-2
	0	0	0		0	0	0
15	3	3	0	50	2	0	-2
	3	3	0		0	0	0
	0	0	0		5	5	0
	2	3	1		2	2	0
	0	0	0		0	0	0
20	0	0	0	55	3	1	-2
	2	3	1		0	0	0
	0	0	0		8	7	-1
	7	7	0		0	0	0
	0	0	0		9	10	1
25	0	3	3	60	1	1	0
	2	3	1		3	1	-2
	0	3	3		2	2	0
	5	4	-1		0	0	0
	0	0	0		4	4	0
30	5	6	1				
	1	0	-1				
	6	7	1				
	1	0	-1				
	0	0	0				

TH65 & 53rd St. Queue length study from tape 4/4/91
 16:45-18:45 (Tape 2)

15 second QUEUE LENGTH Counts, sampled every minute

Time (min)	Manual Count	IMP Count	Diff erence	Time (min)	Manual Count	IMP Count	Diff erence
1	0	0	0	35	5	5	0
	1	1	0		3	0	-3
	0	0	0		11	9	-2
	0	0	0		0	0	0
5	0	0	0		1	0	-1
	3	3	0	40	0	0	0
	0	0	0		0	0	0
	0	0	0		2	2	0
	0	0	0		0	0	0
10	5	0	-5		1	0	-1
	1	1	0	45	5	1	-4
	0	0	0		1	1	0
	2	2	0		9	7	-2
	0	0	0		0	0	0
15	1	0	-1		9	8	-1
	5	3	-2	50	0	0	0
	0	0	0		6	5	-1
	0	0	0		0	0	0
	3	2	-1		1	0	-1
20	0	0	0		11	5	-6
	5	5	0	55	0	0	0
	0	0	0		12	7	-5
	0	0	0		0	0	0
	8	9	1		6	6	0
25	0	0	0		0	0	0
	3	0	-3	60	3	2	-1
	0	0	0		5	7	2
	1	1	0		2	2	0
	0	0	0		8	10	2
30	2	1	-1				
	7	5	-2				
	0	0	0				
	6	10	4				
	0	0	0				

TH65 & 53rd St. Primary Stops study from tape 4/7/91
 11:40-1:40 (Tape 1)

15 second PRIMARY STOP Counts, sampled every minute

Time (min)	Manual Count	IMP Count	Diff erence	Time (min)	Manual Count	IMP Count	Diff erence
1	0	0	0	35	0	0	0
	0	0	0		2	3	1
	0	0	0		0	0	0
	4	4	0		6	8	2
5	0	0	0	40	0	1	1
	0	0	0		8	1	-7
	1	1	0		0	3	3
	0	0	0		1	0	-1
	0	0	0		1	0	-1
10	0	0	0	45	2	1	-1
	1	2	1		0	0	0
	1	1	0		0	0	0
	1	0	-1		0	0	0
	3	3	0		0	0	0
15	0	0	0	50	0	0	0
	0	0	0		5	0	-5
	0	0	0		0	0	0
	4	6	2		0	0	0
	3	2	-1		0	1	1
20	3	0	-3	55	0	0	0
	1	2	1		2	4	2
	0	0	0		1	1	0
	0	0	0		0	0	0
	1	0	-1		1	2	1
25	4	4	0	60	0	0	0
	0	0	0		1	1	0
	1	0	-1		0	0	0
	1	0	-1		3	3	0
	6	6	0				
30	1	0	-1				
	0	0	0				
	0	0	0				
	1	0	-1				
	0	0	0				

TH65 & 53rd St. Primary Stops study from tape 4/4/91
 16:45-18:45 (Tape 2)

15 second PRIMARY STOP Counts, sampled every minute

Time (min)	Manual Count	IMP Count	Diff erence	Time (min)	Manual Count	IMP Count	Diff erence
1	0	0	0	35	3	2	-1
	3	3	0		6	4	-2
	0	0	0		5	6	1
	0	0	0		2	2	0
5	0	0	0	40	0	0	0
	0	0	0		2	0	-2
	3	2	-1		0	0	0
	0	0	0		1	2	1
	0	0	0		5	0	-5
10	8	3	-5	45	0	0	0
	1	0	-1		0	4	4
	3	0	-3		0	0	0
	2	0	-2		2	1	-1
	0	0	0		0	0	0
15	0	0	0	50	5	6	1
	3	5	2		0	0	0
	0	0	0		1	0	-1
	0	0	0		7	1	-6
	3	2	-1		0	0	0
20	0	0	0	55	0	0	0
	4	5	1		0	1	1
	0	2	2		5	5	0
	0	0	0		0	0	0
	3	1	-2		1	0	-1
25	0	0	0	60	0	0	0
	1	0	-1		0	0	0
	0	0	0		2	2	0
	0	0	0		0	0	0
	0	0	0		4	5	1
30	2	4	2		0	0	0
	0	0	0				
	0	9	9				
	1	1	0				
	0	0	0				

TH65 & 53rd St - TT (veh-mi) Comparison

Time min	Tape 1		Tape 2	
	Manual TT	IMP TT	Manual TT	IMP TT
5	2.45	2.25	3.34	3.18
10	1.86	1.79	5.63	5.10
15	2.94	2.97	3.04	3.78
20	3.30	3.12	5.02	4.37
25	3.43	2.99	4.37	4.30
30	2.65	2.26	4.16	4.90
35	2.96	2.39	4.49	4.37
40	3.05	3.63	4.69	4.70
45	3.03	2.69	4.03	3.99
50	3.72	3.22	5.17	4.89
55	3.47	2.76	4.44	4.44
60	3.44	3.00	4.37	4.52

TH65 & 53rd St - TTT (veh-hrs) Comparison

Time min	Tape 1		Tape 2	
	Manual TTT	IMP TTT	Manual TTT	IMP TTT
5	0.15	0.21	0.17	0.20
10	0.11	0.21	0.31	0.43
15	0.36	0.31	0.18	0.22
20	0.25	0.33	0.31	0.33
25	0.27	0.28	0.34	0.49
30	0.28	0.29	0.26	0.19
35	0.25	0.32	0.39	0.75
40	0.48	0.41	0.58	0.58
45	0.39	0.33	0.30	0.40
50	0.28	0.32	0.50	0.52
55	0.32	0.36	0.38	0.39
60	0.29	0.37	0.33	0.41

TH65 & 53rd St - Fuel Consumption, Emissions and LOS

Tape 1						Tape 2				
Time min	Fuel (gal)	HC (g)	CO (g)	NOX (g)	LOS	Fuel (gal)	HC (g)	CO (g)	NOX (g)	LOS
5	0.86	6.41	12.7	0.41	B	0.83	15.9	15.2	0.61	B
10	0.87	9.82	11.4	0.34	A	1.79	23.9	27.7	0.94	B
15	1.31	11.0	18.0	0.53	B	0.93	21.8	17.6	0.73	A
20	1.41	11.3	19.2	0.56	B	1.37	23.7	22.5	0.84	B
25	1.19	8.29	11.3	0.53	B	2.06	23.7	27.3	0.81	B
30	1.18	6.18	14.8	0.39	B	0.77	44.8	19.7	1.00	A
35	1.36	2.72	16.5	0.38	B	3.11	17.9	35.8	0.78	B
40	1.77	13.2	23.1	0.65	B	2.46	22.1	31.7	0.86	B
45	1.37	8.62	17.5	0.47	B	1.70	21.4	23.7	0.75	A
50	1.35	9.37	18.8	0.56	A	2.22	22.8	30.0	0.90	B
55	1.52	6.25	19.0	0.46	B	1.61	18.4	23.9	0.81	B
60	1.56	12.1	19.8	0.54	C	1.77	24.5	25.6	0.86	B

26th Street Tape - Detection Accuracy Lane 1

Detection ratio (det ratio) is defined by the expression

$$((\text{Autoscope count} - \text{manual count}) / \text{manual count}) * 100.0 + 100.0$$

The V/C ratio is given by the expression

$$(\text{average manual 5-minute lane volume}) * 12 / 2300$$

where the average manual 5-minute lane volume is computed from
 $(\text{detector 0 manual count} + \text{detector 4 manual count}) / 2$

Time min	Lane V/C	Detector 4		Det Ratio	Detector 0		Det Ratio
		Manual Volume	Autoscope Volume		Manual Volume	Autoscope Volume	
5	0.49	85	89	104.7	103	97	94.2
10	0.50	104	105	101.0	88	90	102.3
15	0.64	131	132	100.8	114	117	102.6
20	0.85	163	165	101.2	164	147	89.6
25	0.88	171	163	95.3	167	122	73.1
30	0.83	162	163	100.6	158	132	83.6
35	0.80	148	150	101.4	157	115	73.3
40	0.77	143	142	99.3	153	123	80.4
45	0.73	143	144	100.7	137	104	75.9
50	0.81	157	154	98.1	153	102	66.7
55	0.86	168	170	101.2	162	127	78.4
60	0.87	162	159	98.1	170	110	64.7
65	0.77	140	146	104.3	156	133	85.3

26th Street Tape - Detection Accuracy Lane 2

Detection ratio (det ratio) is defined by the expression

$$\frac{((\text{Autoscope count} - \text{manual count}) / \text{manual count}) * 100.0 + 100.0}{}$$

The V/C ratio is given by the expression

$$\frac{(\text{average manual 5-minute lane volume}) * 12}{2300}$$

where the average manual 5-minute lane volume is computed from
 $\frac{(\text{detector 1 manual count} + \text{detector 5 manual count})}{2}$

Time min	Lane V/C	Detector 5			Detector 1		
		Manual Volume	Autoscope Volume	Det Ratio	Manual Volume	Autoscope Volume	Det Ratio
5	0.65	118	117	99.2	131	114	87.0
10	0.81	165	160	97.0	144	138	97.2
15	0.85	165	166	100.6	161	158	98.1
20	1.03	205	204	99.5	190	163	85.8
25	1.06	194	194	100.0	213	167	78.4
30	0.96	188	192	102.1	179	141	78.8
35	0.89	161	161	100.0	182	153	84.1
40	0.78	148	149	100.7	151	119	78.8
45	0.79	152	150	98.7	150	121	80.7
50	0.88	180	178	98.9	156	112	71.8
55	0.96	177	179	101.1	191	164	85.9
60	0.87	162	159	98.2	173	138	76.3
65	1.04	211	207	98.1	186	144	77.4

26th Street Tape - Lane Space Mean Speed (mph) Comparison

Time min	Lane 2		Lane 1	
	Manual Speed	IMP Speed	Manual Speed	IMP Speed
5	50.1	52.3	50.5	50.8
10	50.1	50.1	51.2	50.6
15	48.6	41.4	48.6	42.2
20	36.4	34.8	36.5	36.2
25	35.4	32.8	36.2	35.6
30	28.8	26.2	36.2	35.6
35	23.5	22.8	30.2	30.8
40	18.6	18.3	25.8	23.0
45	17.5	17.9	19.4	19.2
50	20.0	23.9	23.2	24.0
55	34.1	37.0	33.8	35.4
60	25.9	21.6	28.2	29.0
65	23.3	32.9	33.9	41.2

26th Street Tape - Total Travel (veh-mi) Comparison

Time min	Lane 2		Lane 1	
	Manual TT	IMP TT	Manual TT	IMP TT
5	5.66	5.77	4.27	4.73
10	7.02	6.27	4.36	4.45
15	7.41	7.27	5.57	5.77
20	8.98	8.18	7.43	6.91
25	9.25	8.0	7.68	6.32
30	8.34	7.41	7.27	6.88
35	7.8	7.0	6.93	6.05
40	6.79	6.05	6.73	6.18
45	6.86	5.82	6.36	5.5
50	7.64	6.68	7.05	6.0
55	8.36	7.91	7.5	6.55
60	7.61	6.77	7.55	6.18
65	9.02	8.27	6.73	6.64

26th Street Tape - Delay (veh-hrs) Comparison

Time min	Lane 2		Lane 1	
	Manual Delay	IMP Delay	Manual Delay	IMP Delay
5	0.02	0.01	0.01	0.01
10	0.02	0.02	0.01	0.01
15	0.03	0.05	0.02	0.04
20	0.10	0.10	0.08	0.08
25	0.11	0.11	0.08	0.07
30	0.15	0.16	0.12	0.11
35	0.20	0.19	0.15	0.16
40	0.25	0.23	0.23	0.17
45	0.28	0.23	0.22	0.19
50	0.25	0.17	0.19	0.15
55	0.11	0.08	0.10	0.08
60	0.17	0.20	0.17	0.11
65	0.24	0.11	0.09	0.05

Lyndale Ave Tape - Lane Delay (veh-sec) Comparison

	Lane 2		Lane 3	
Time min	Manual Delay	IMP Delay	Manual Delay	IMP Delay
-----	-----	-----	-----	-----
5	0.07	0.12	0.04	0.07
10	0.08	0.14	0.06	0.10
15	0.11	0.14	0.16	0.14
20	0.23	0.21	0.19	0.21
25	0.17	0.25	0.20	0.22
30	0.16	0.21	0.13	0.19
35	0.12	0.19	0.14	0.17
40	0.23	0.17	0.18	0.18
45	0.18	0.20	0.20	0.21
50	0.22	0.16	0.15	0.20
55	0.21	0.15	0.13	0.18
60	0.15	0.14	0.22	0.14
65	0.13	0.16	0.10	0.13

Lyndale Ave Tape - Fuel Consumption, Emissions and LOS

Lane 2						Lane 3				
Time min	Fuel (gal)	HC (g)	CO (g)	NOX (g)	LOS	Fuel (gal)	HC (g)	CO (g)	NOX (g)	LOS
5	0.29	0.85	27.7	3.66	E	0.31	0.89	29.3	3.83	F
10	0.39	1.10	29.1	4.50	F	0.36	1.04	36.0	4.55	F
15	0.36	1.04	34.9	4.51	F	0.35	1.03	35.6	4.50	F
20	0.35	0.96	16.4	3.63	F	0.38	1.04	16.5	3.90	F
25	0.38	1.04	11.4	3.74	F	0.36	0.99	12.6	3.61	F
30	0.37	1.01	13.2	3.68	F	0.38	1.05	17.9	3.97	F
35	0.40	1.10	17.7	4.13	F	0.40	1.13	23.2	4.41	F
40	0.35	0.99	23.0	3.96	F	0.38	1.07	26.8	4.35	F
45	0.32	0.86	10.9	3.13	F	0.37	1.00	12.9	3.66	F
50	0.34	0.93	13.3	3.43	F	0.40	1.10	20.2	4.23	F
55	0.25	0.68	11.2	2.57	F	0.32	0.88	14.6	3.32	F
60	0.33	0.93	21.0	3.69	F	0.37	1.05	27.8	4.30	F
65	0.29	0.81	15.6	3.14	F	0.30	0.84	20.8	3.39	F

13. FIGURES

Calculating Delay Using The Input/Output model

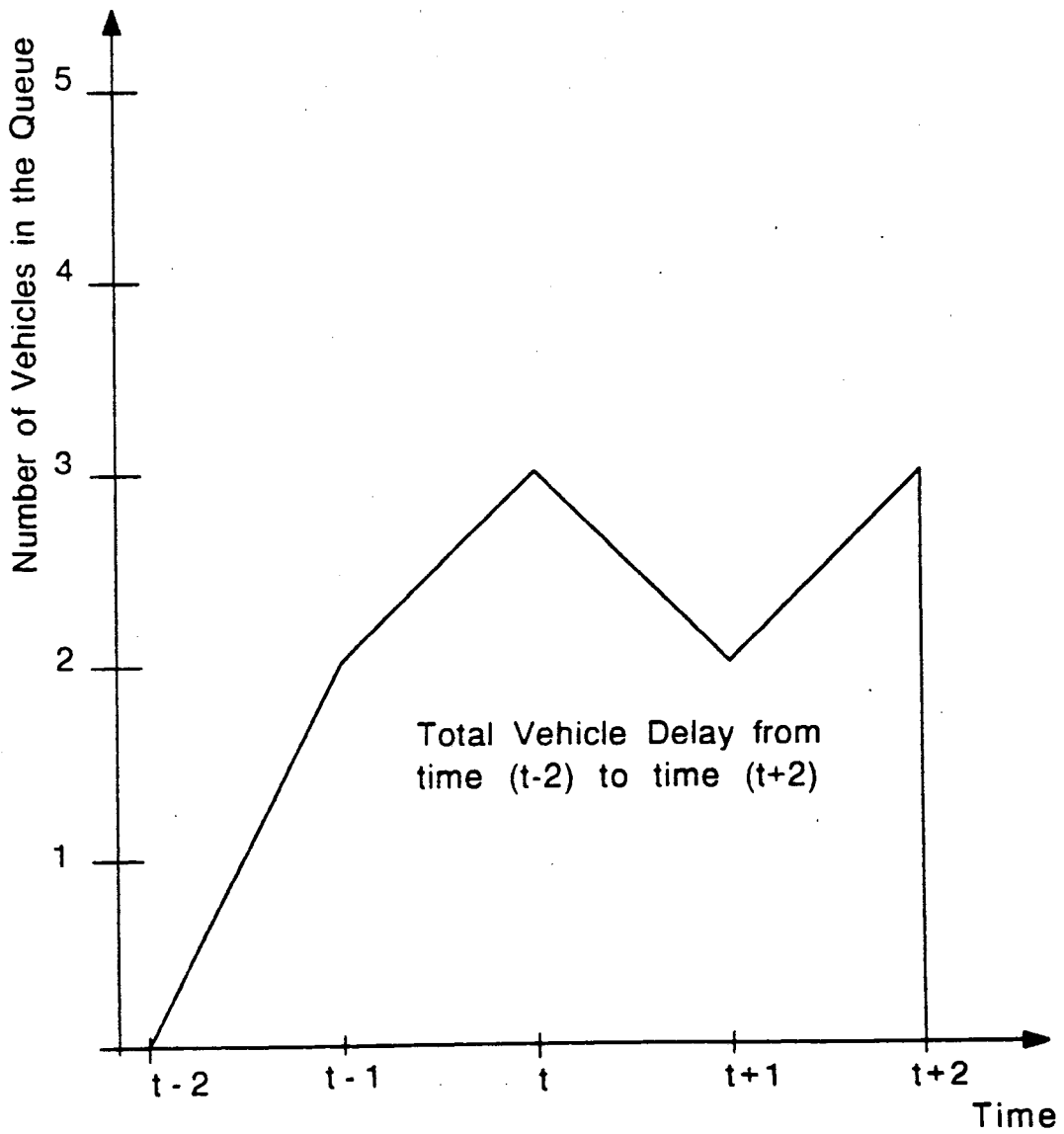


Figure 1

Criteria for Determining Intersection Level of Service

Stopped Delay (SD) Per Vehicle In Seconds	Level of Service
$SD \leq 5$	A
$5 < SD \leq 15$	B
$15 < SD \leq 25$	C
$25 < SD \leq 40$	D
$40 < SD \leq 60$	E
$60 < SD$	F

Figure 2

Criteria for Determining Highway Level of Service

Level of Service	Density (pc/mile/lane)
A	≤ 12
B	≤ 20
C	≤ 30
D	≤ 42
E	≤ 67
F	

Figure 3

TH65 & 53rd Street Testsite Detector Layout

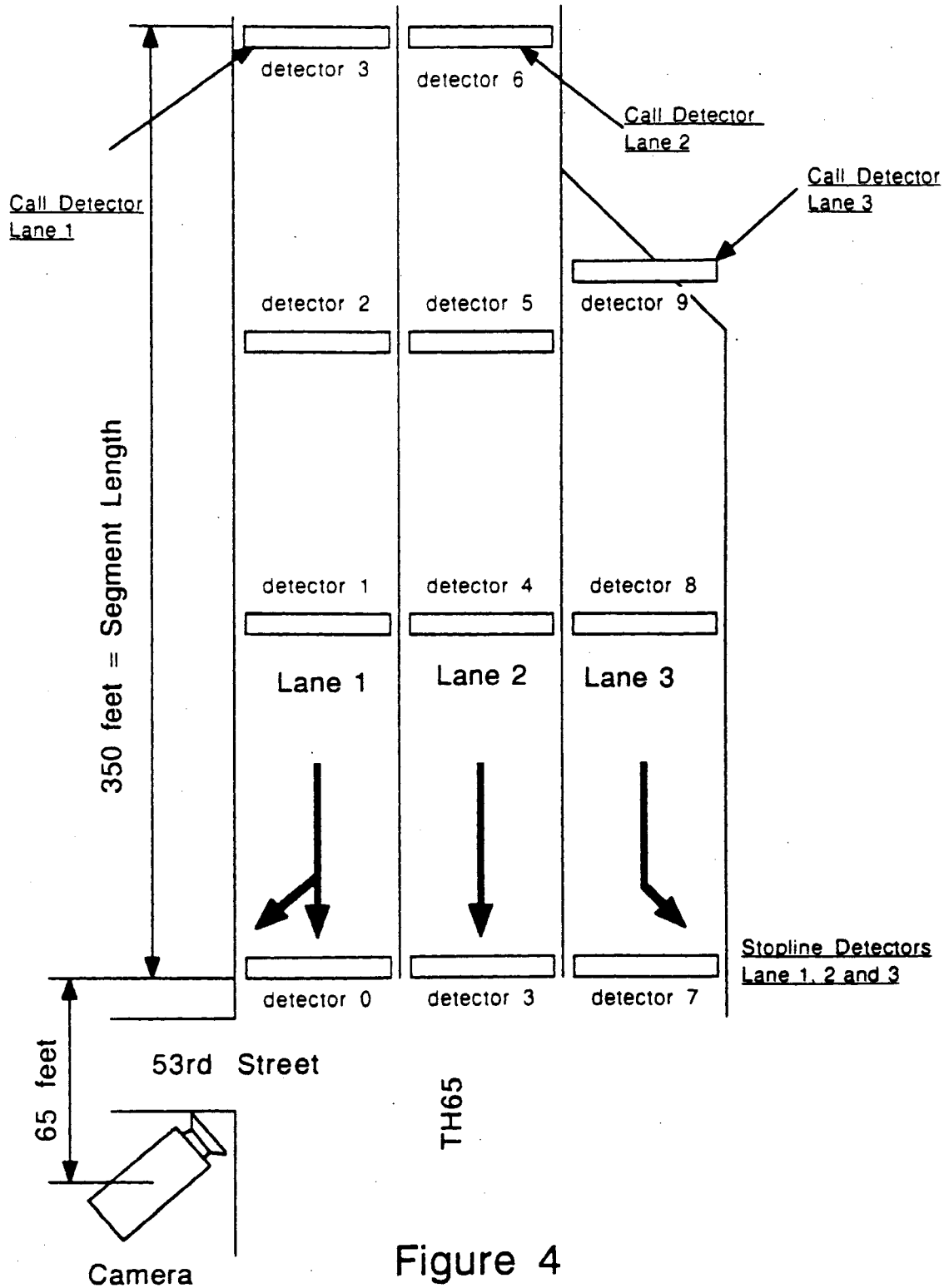


Figure 4

Highway 35W & 26th Street Test Site Detector Layout

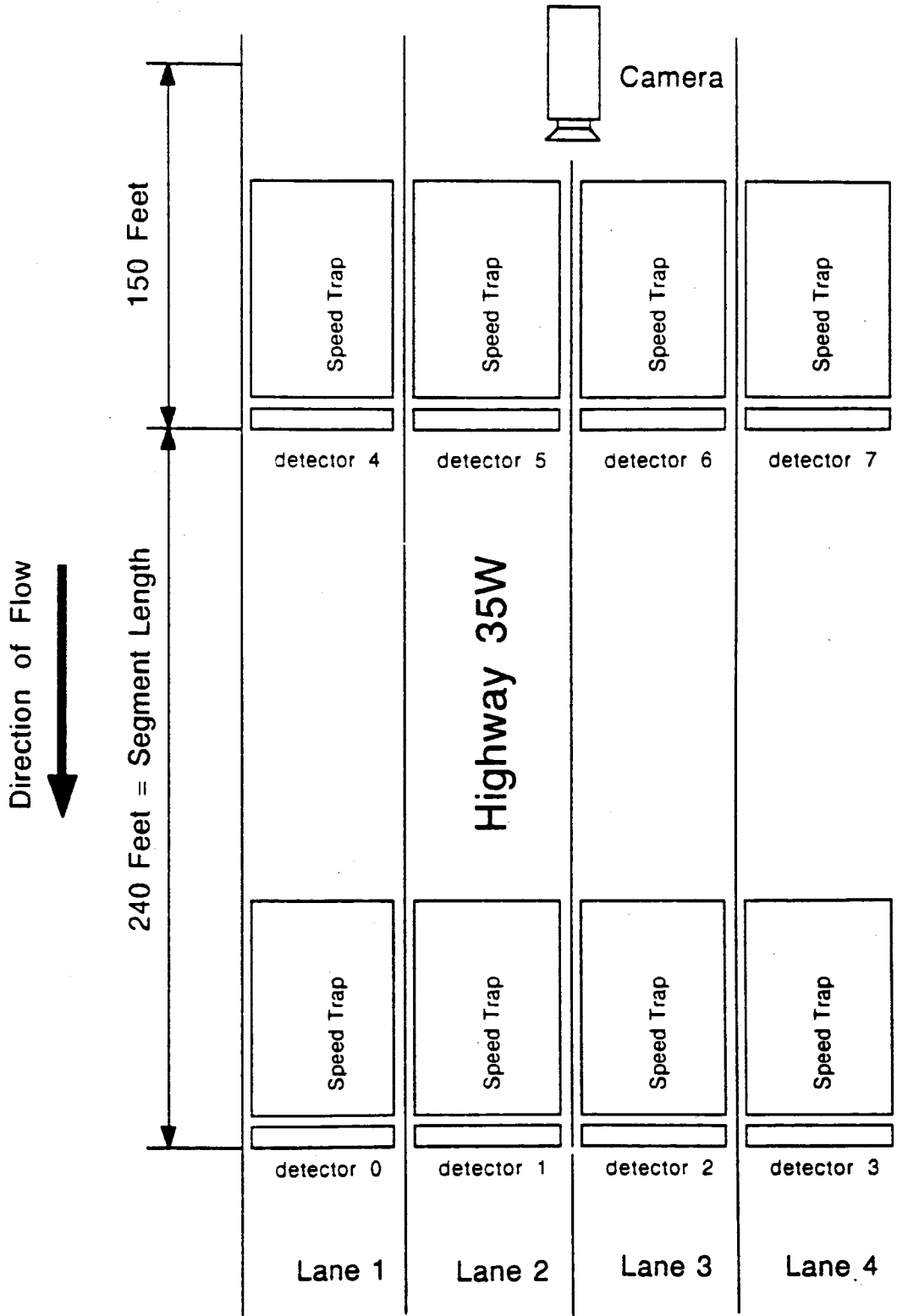


Figure 5
103

Highway 35W & Lyndale Ave Test Site Detector Layout

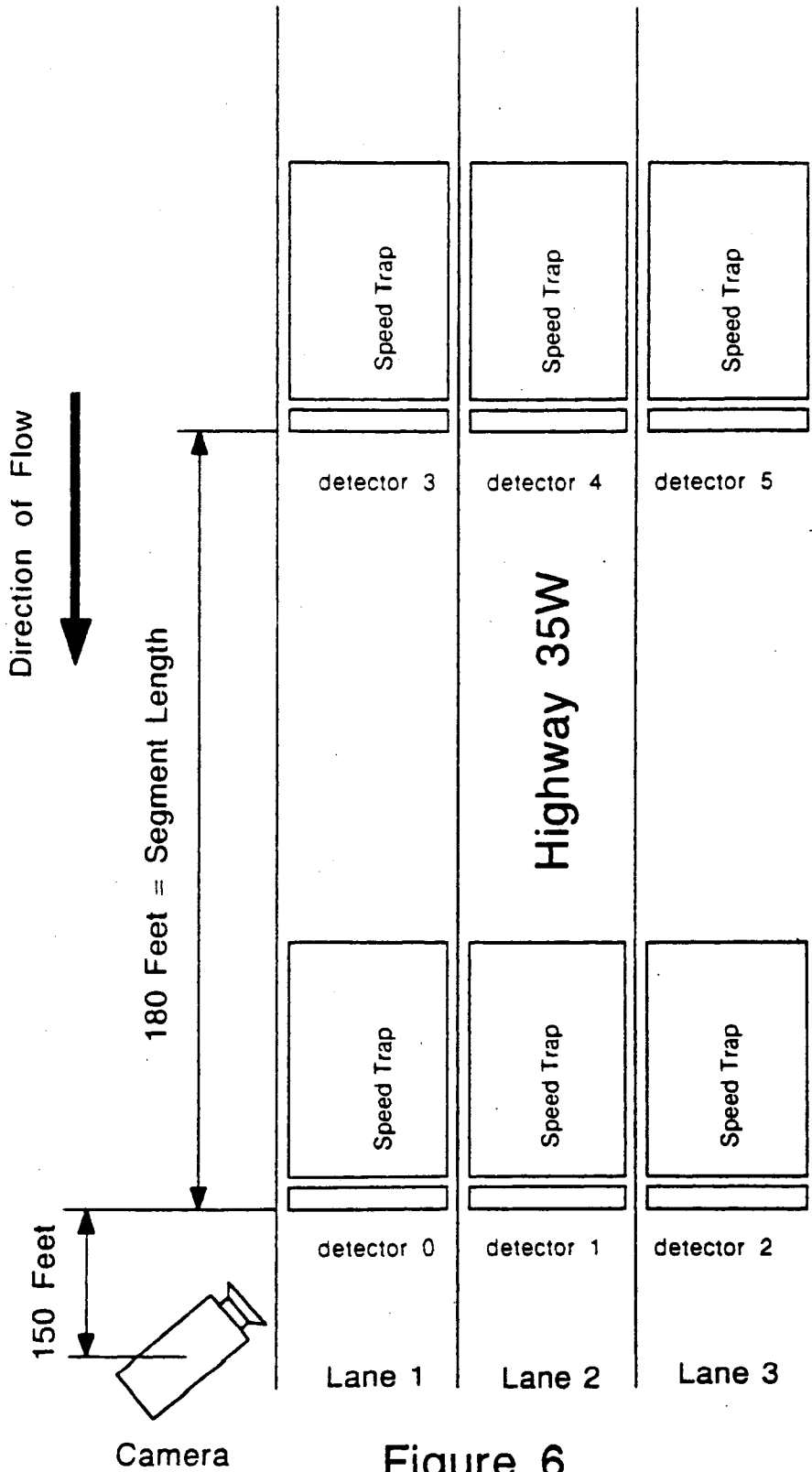


Figure 6

The Compartment Input/Output model

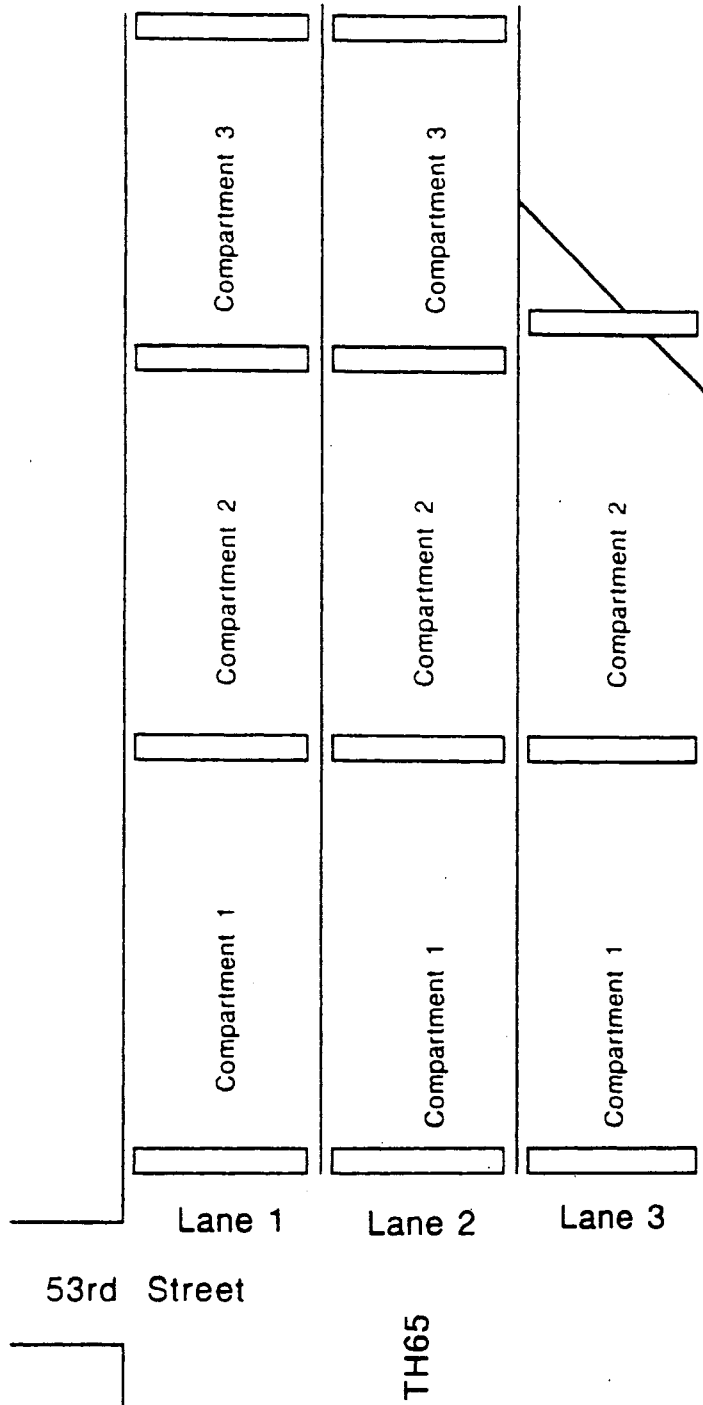


Figure 7

Compartment Input/Output model vehicle counts

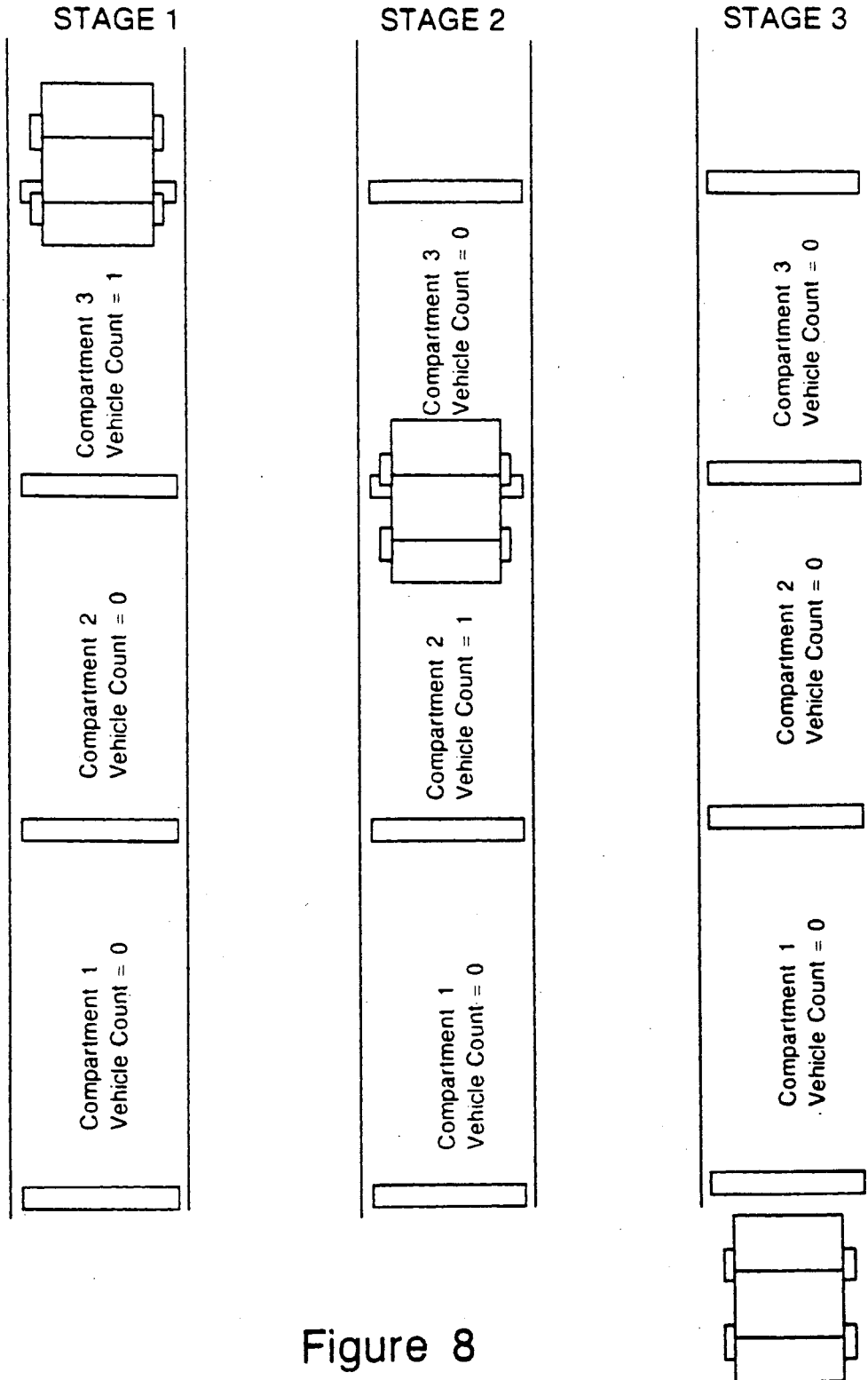


Figure 8

Compartment Input/Output model vehicle counts

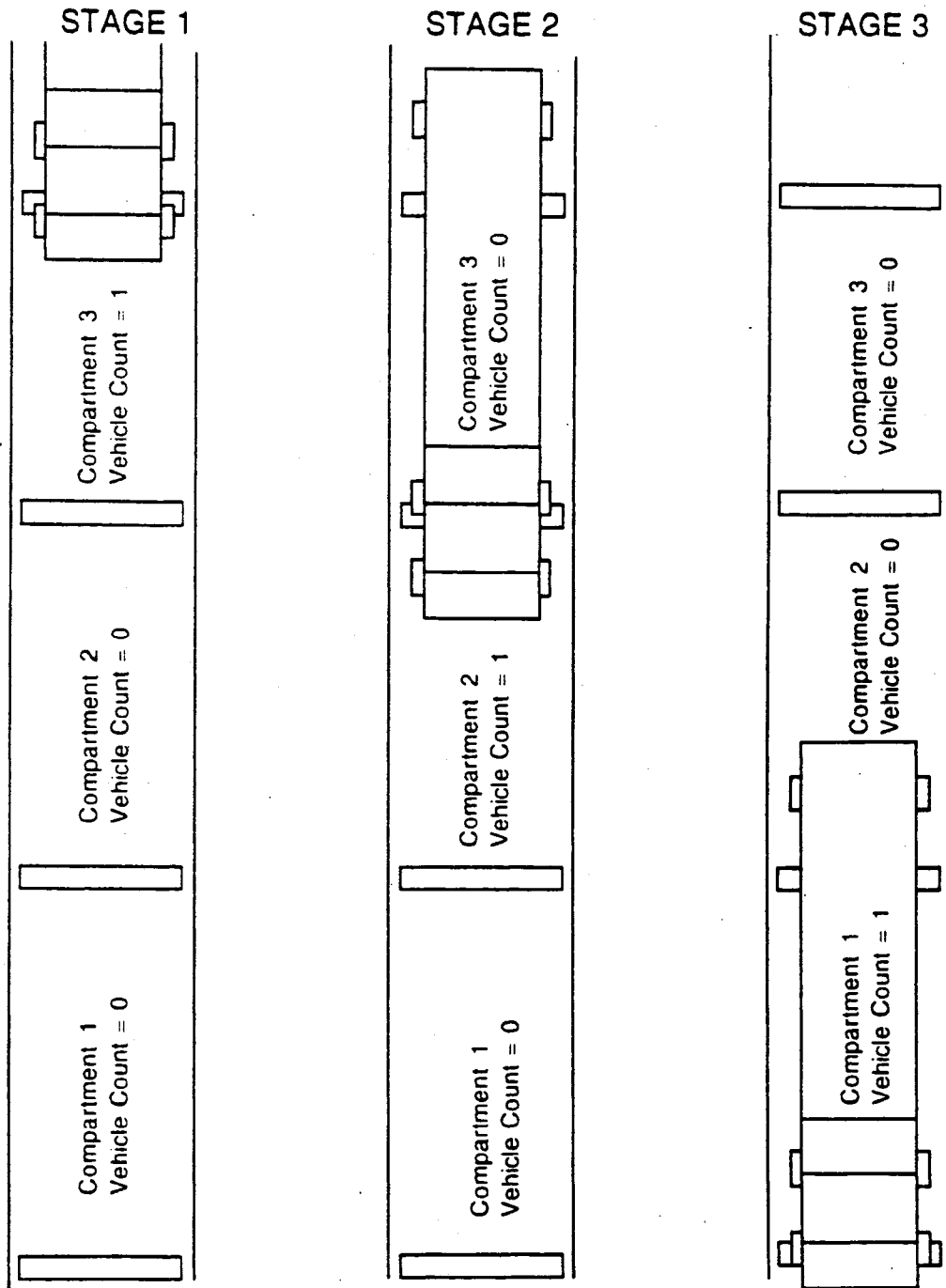


Figure 9
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Calculating total travel at an intersection

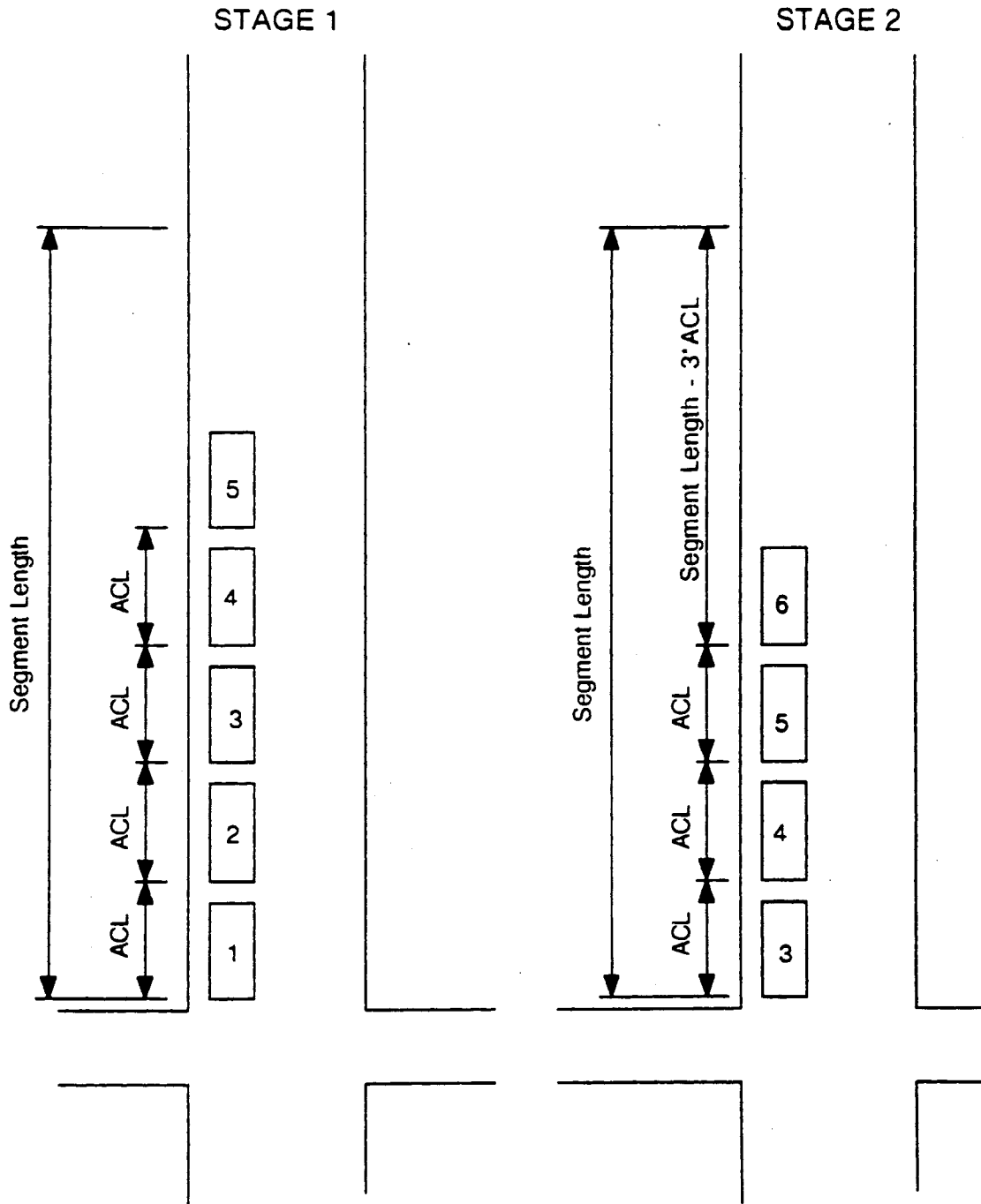


Figure 10

Figure 11
Queue Length Comparison - Int. Tape 1

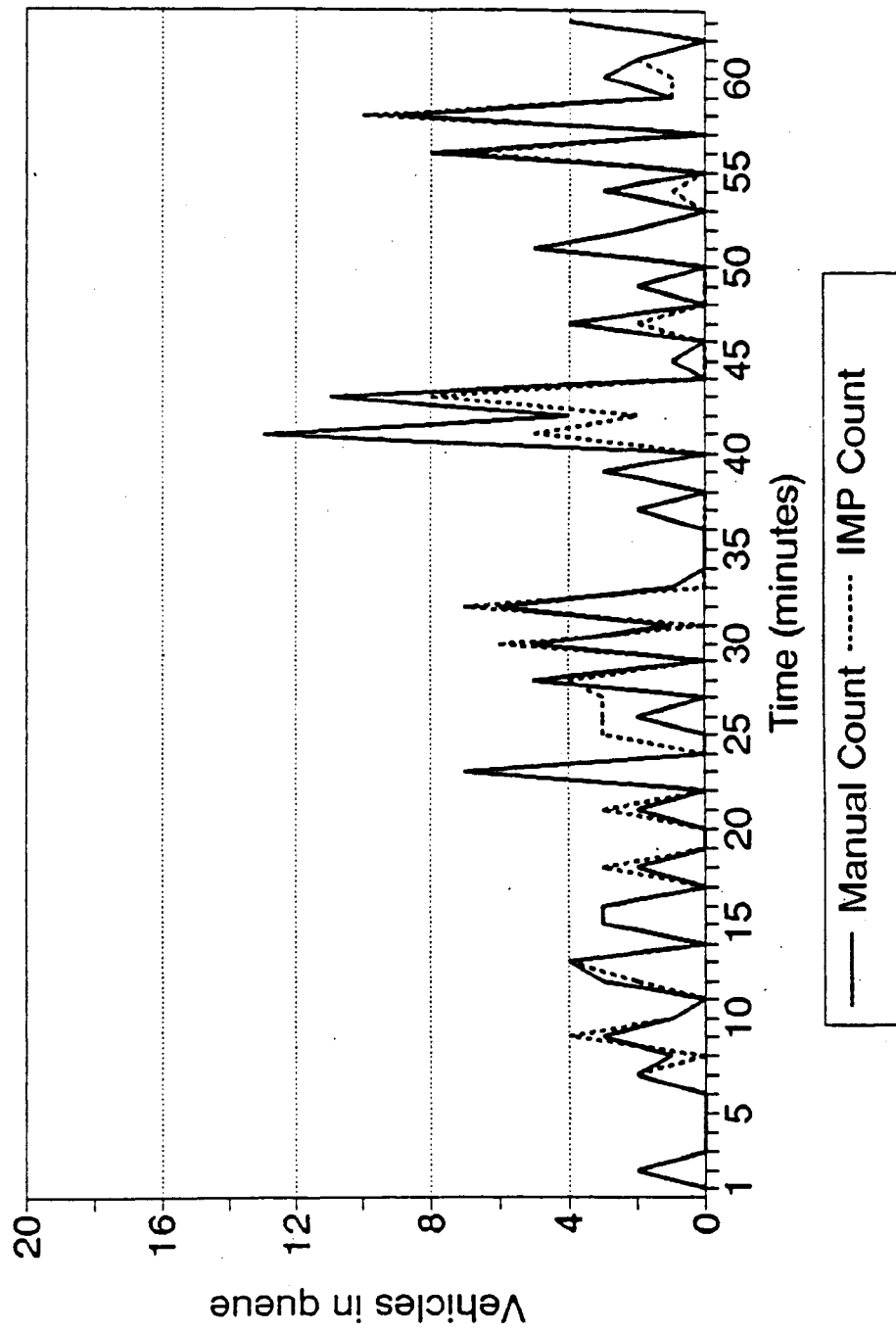


Figure 12
Queue Length Comparison - Int. Tape 2

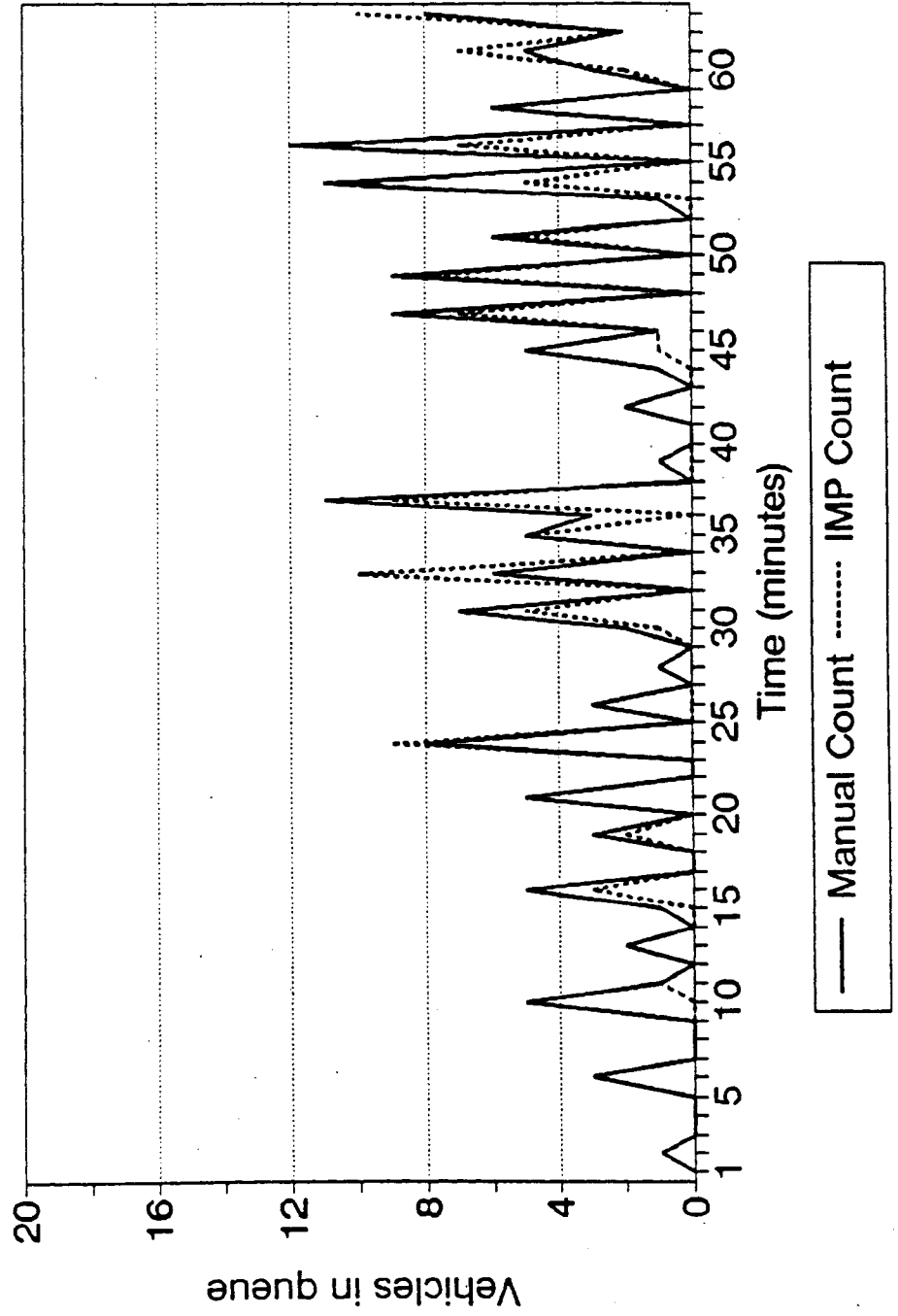


Figure 13

Stops Comparison - Intersection Tape 1

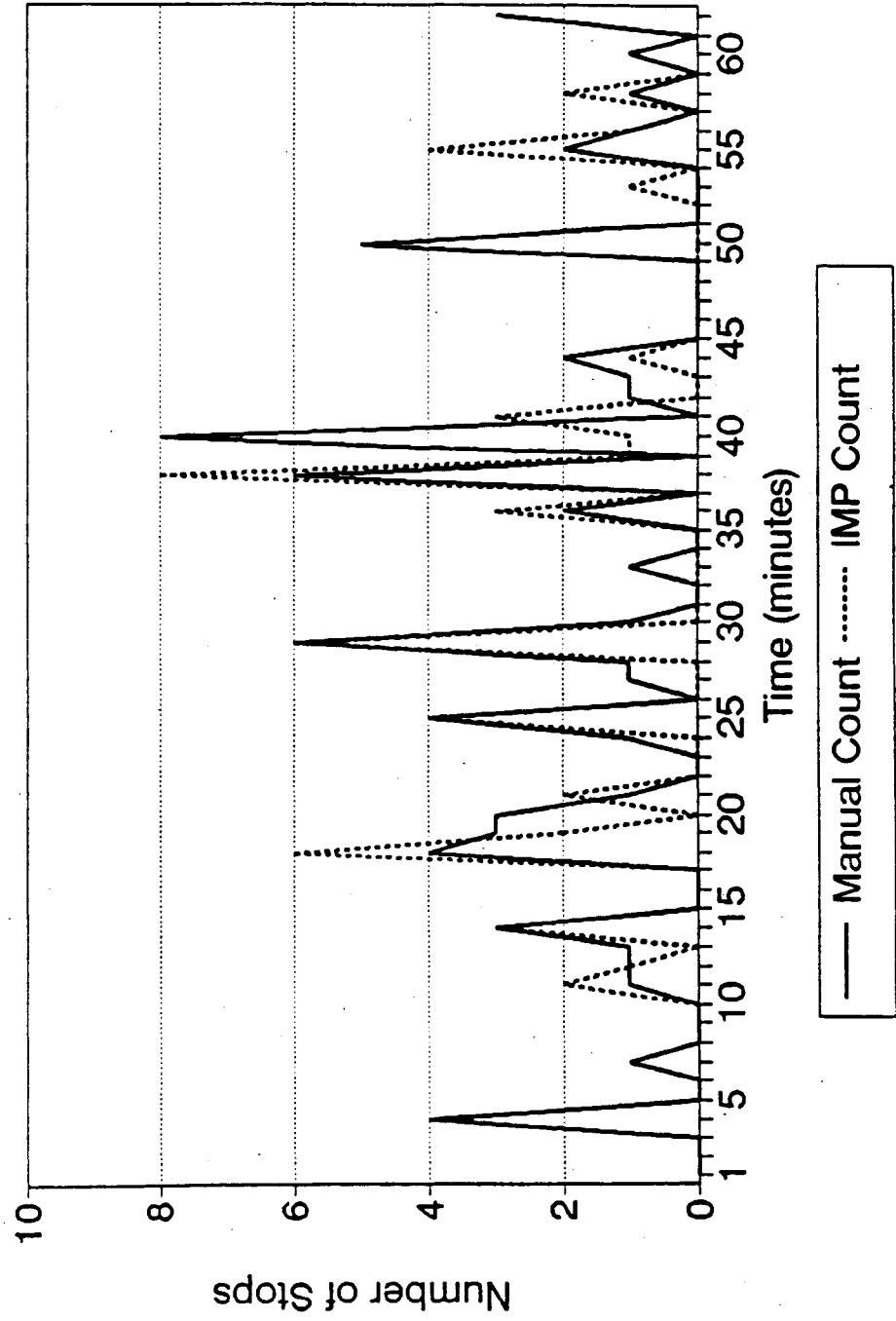


Figure 14
Stops Comparison - Intersection Tape 2

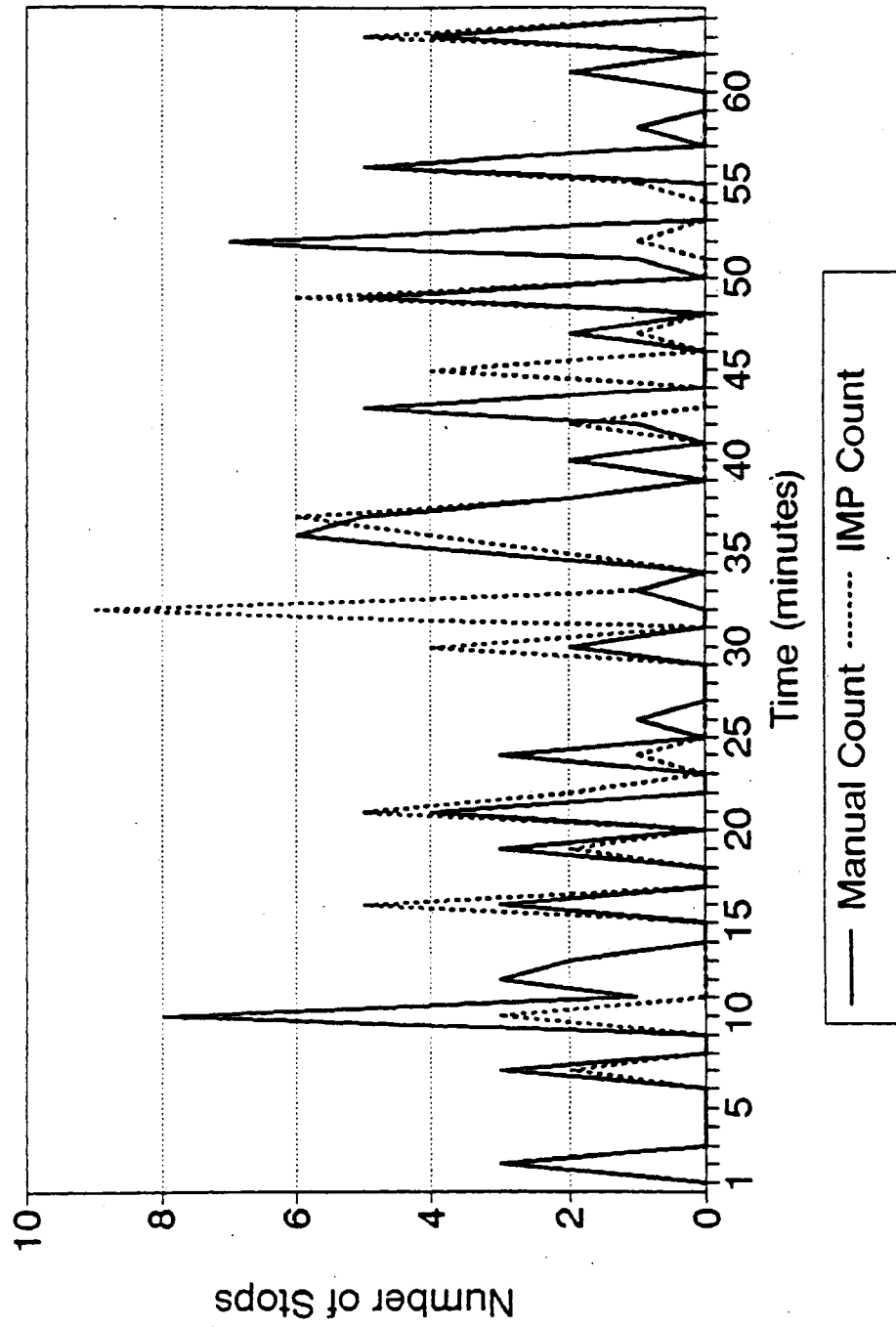


Figure 15
 TT Comparison - Intersection Tape 1

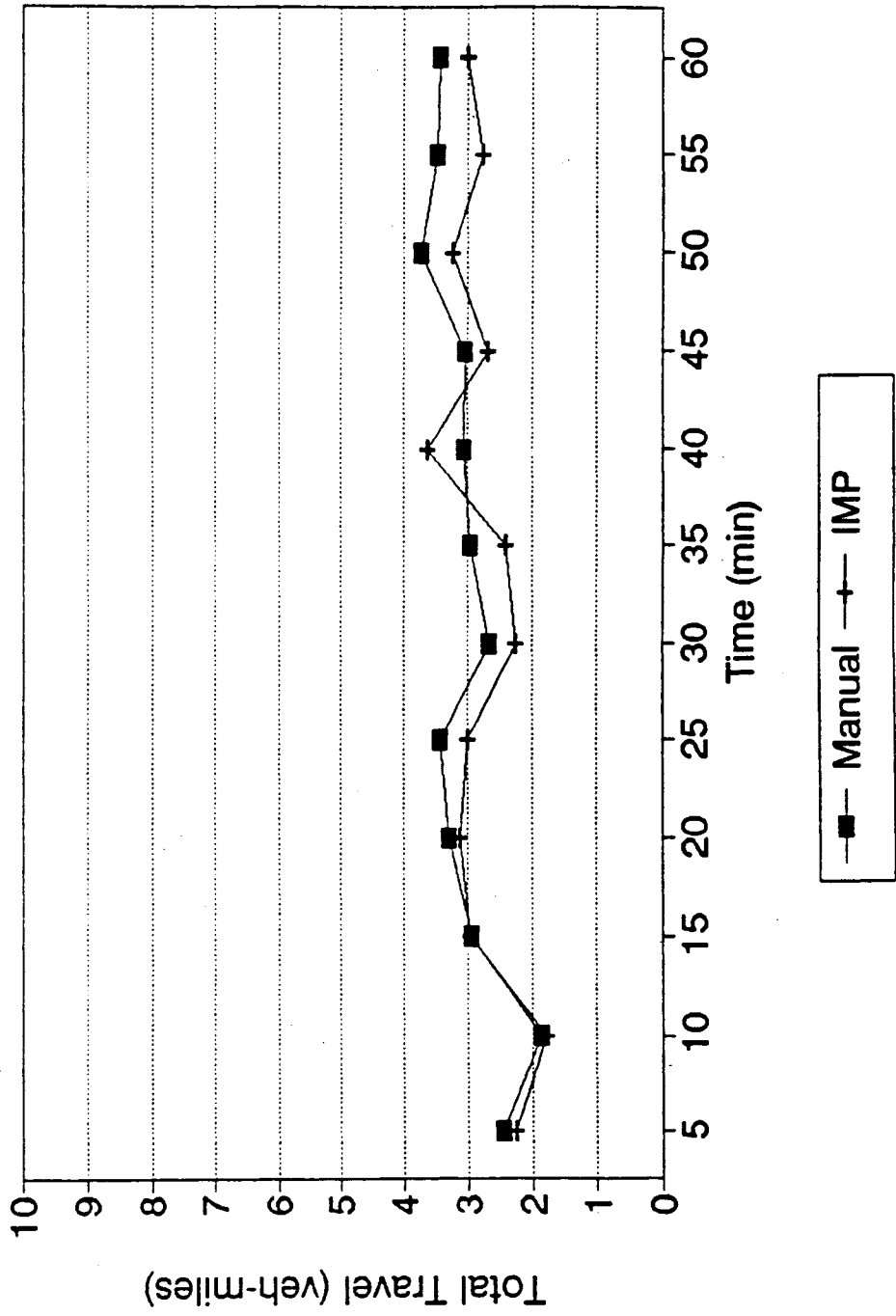


Figure 16
 TT Comparison - Intersection Tape 2

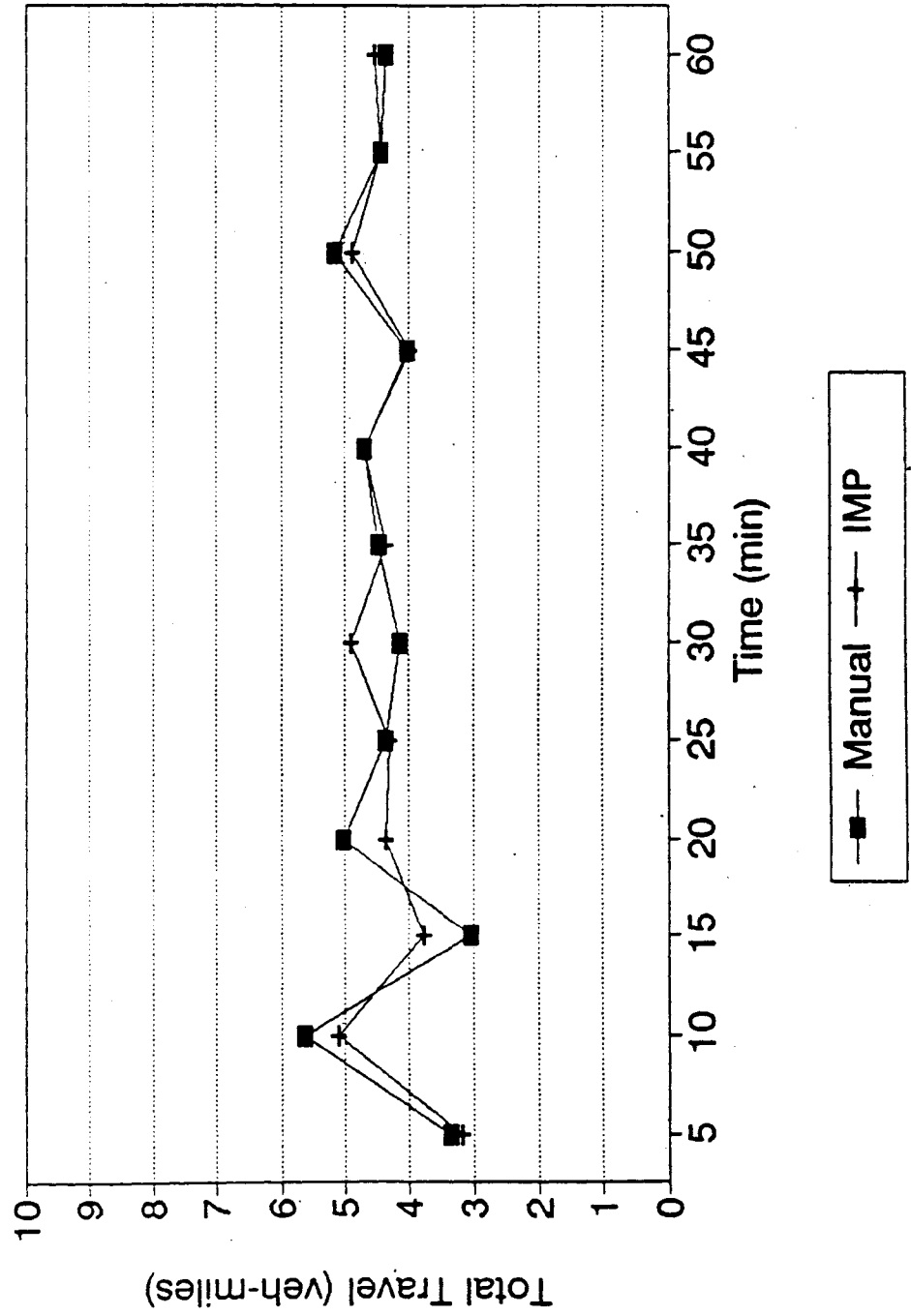


Figure 17

TTT Comparison - Intersection Tape 1

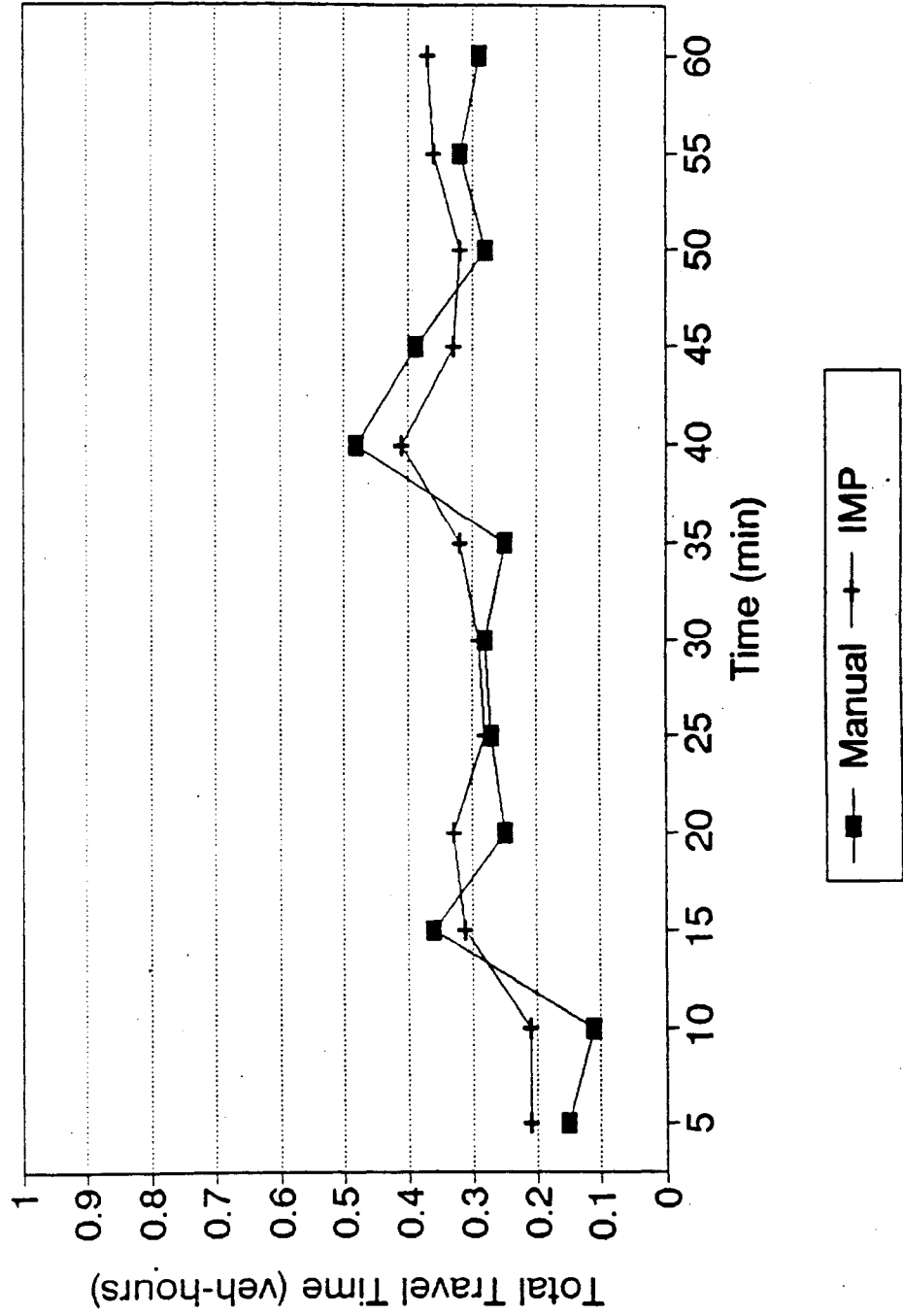


Figure 18

TTT Comparison - Intersection Tape 2

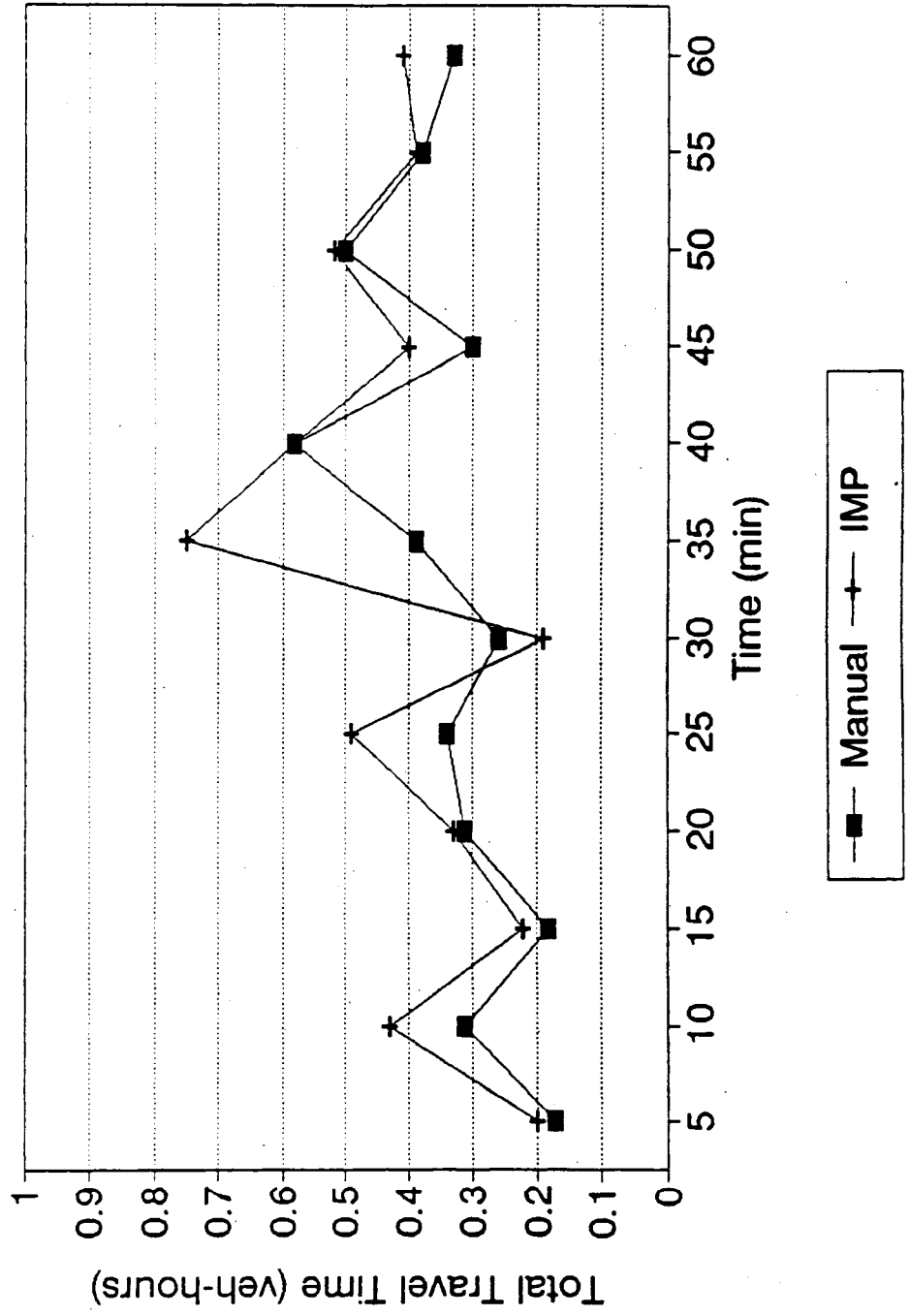


Figure 19
Detection Ratio 26th St Tape

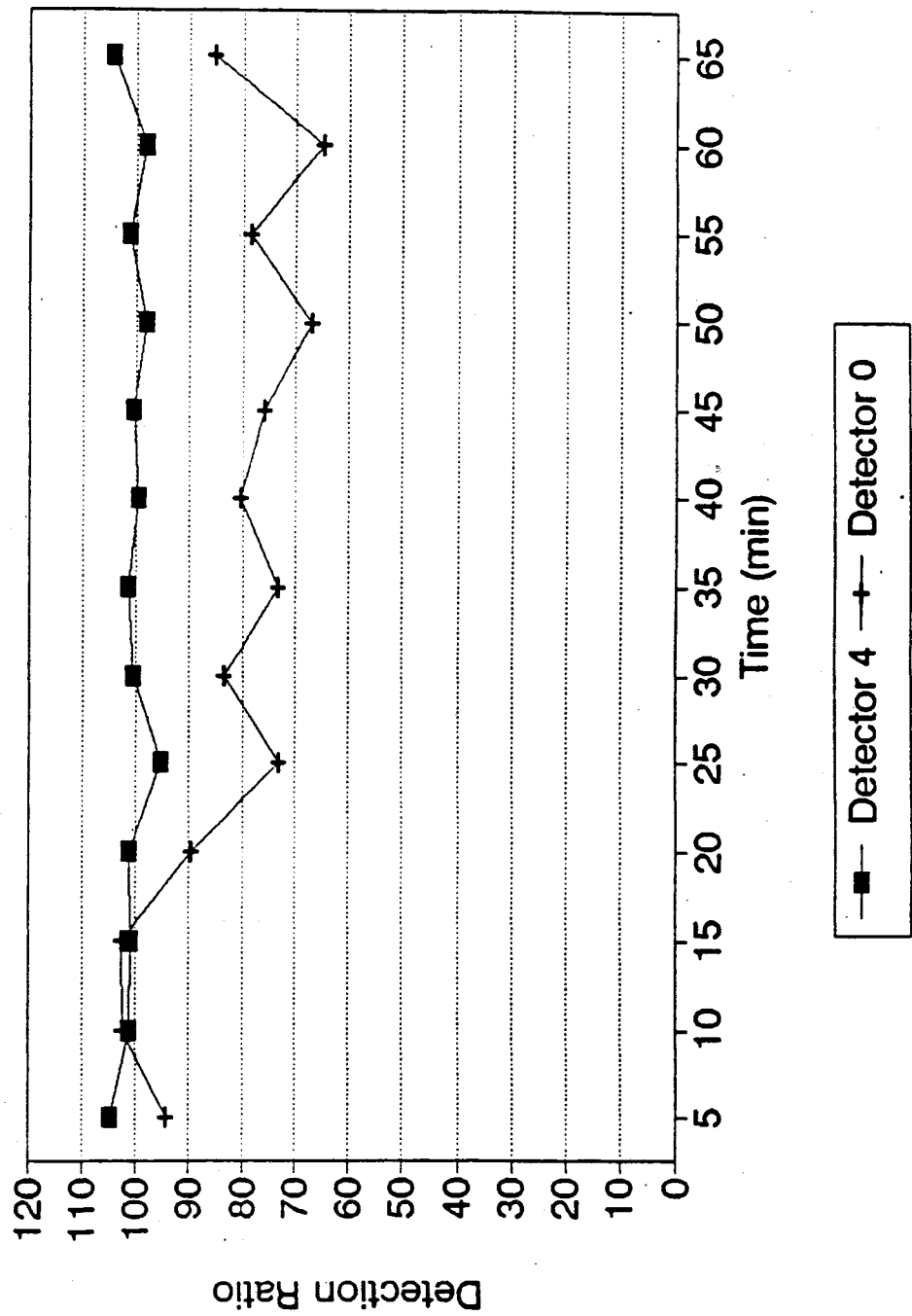


Figure 20
SMS Comparison 26th St Tape Lane 1

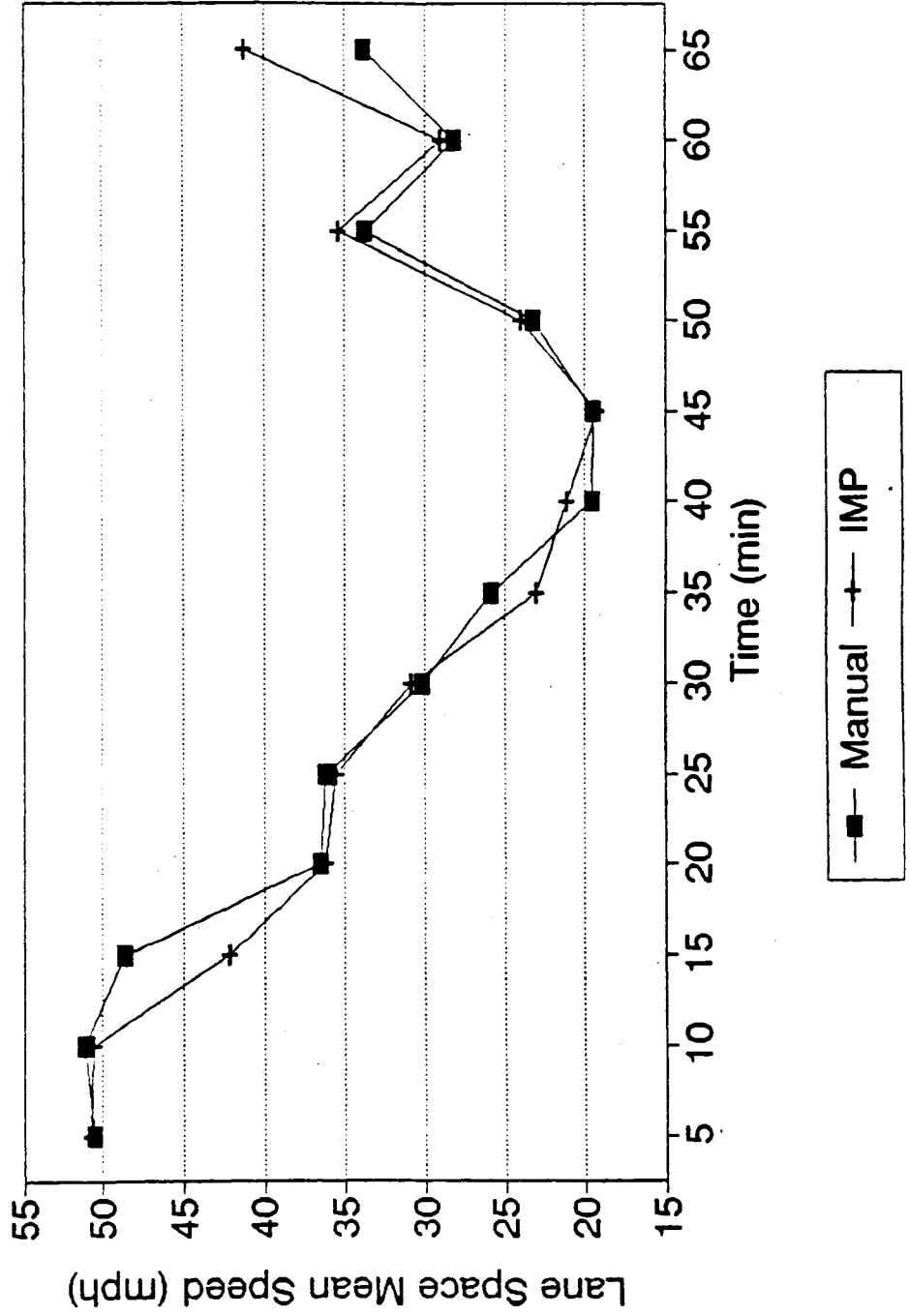


Figure 21
 TT Comparison 26th St Tape Lane 1

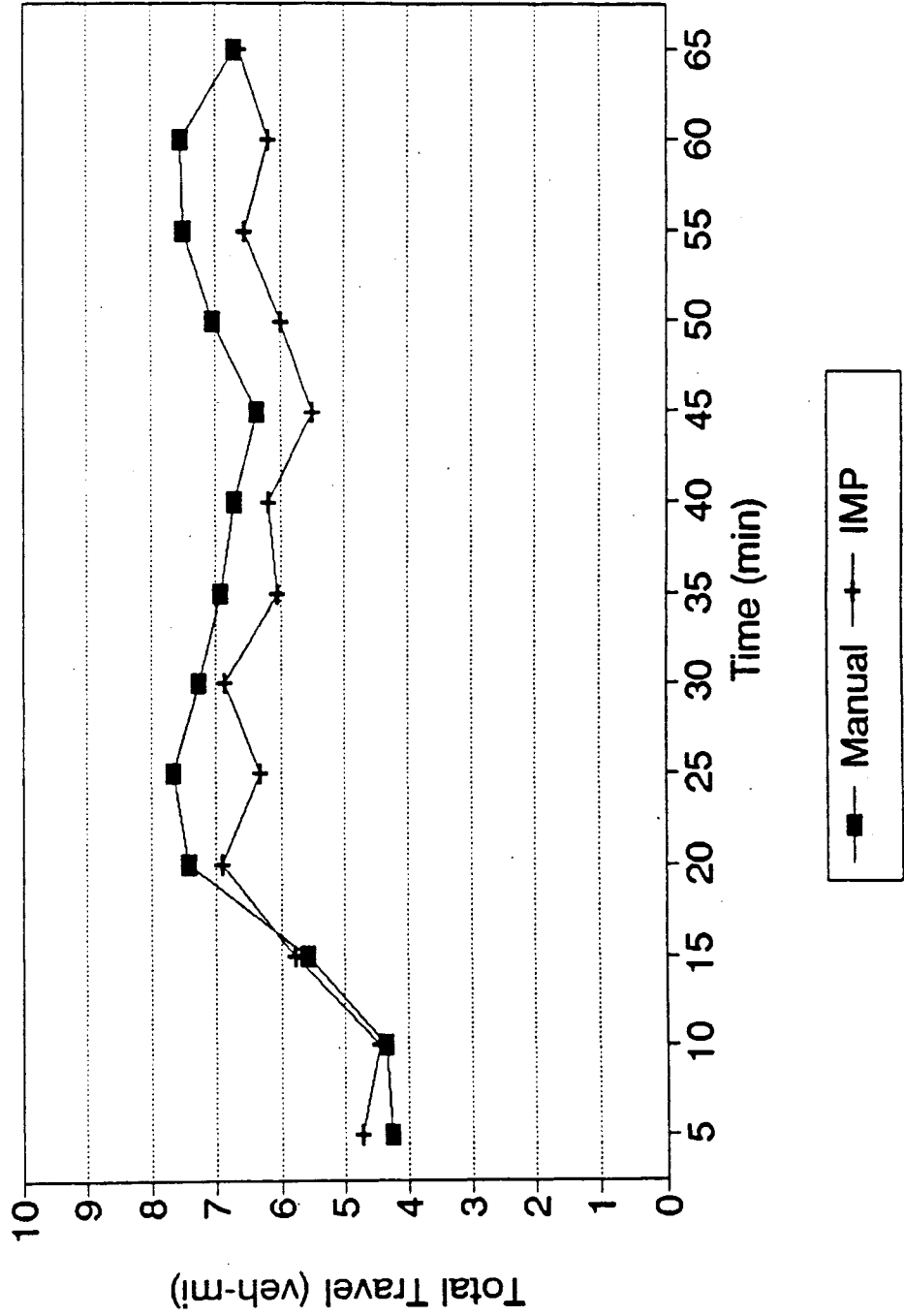


Figure 22
Delay Comparison 26th St Tape Lane 1

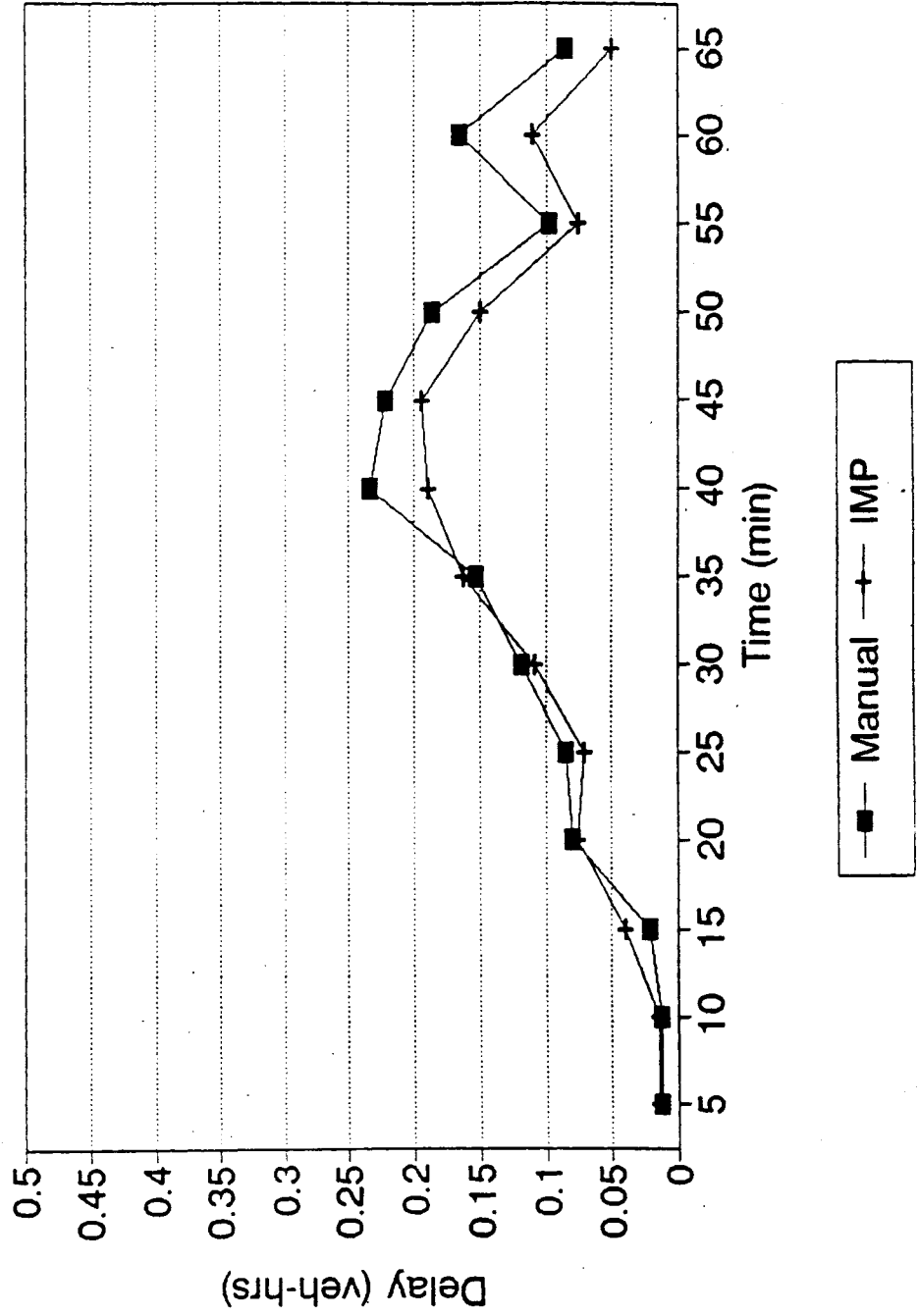


Figure 23

Detection Ratio Lyndale Ave Tape

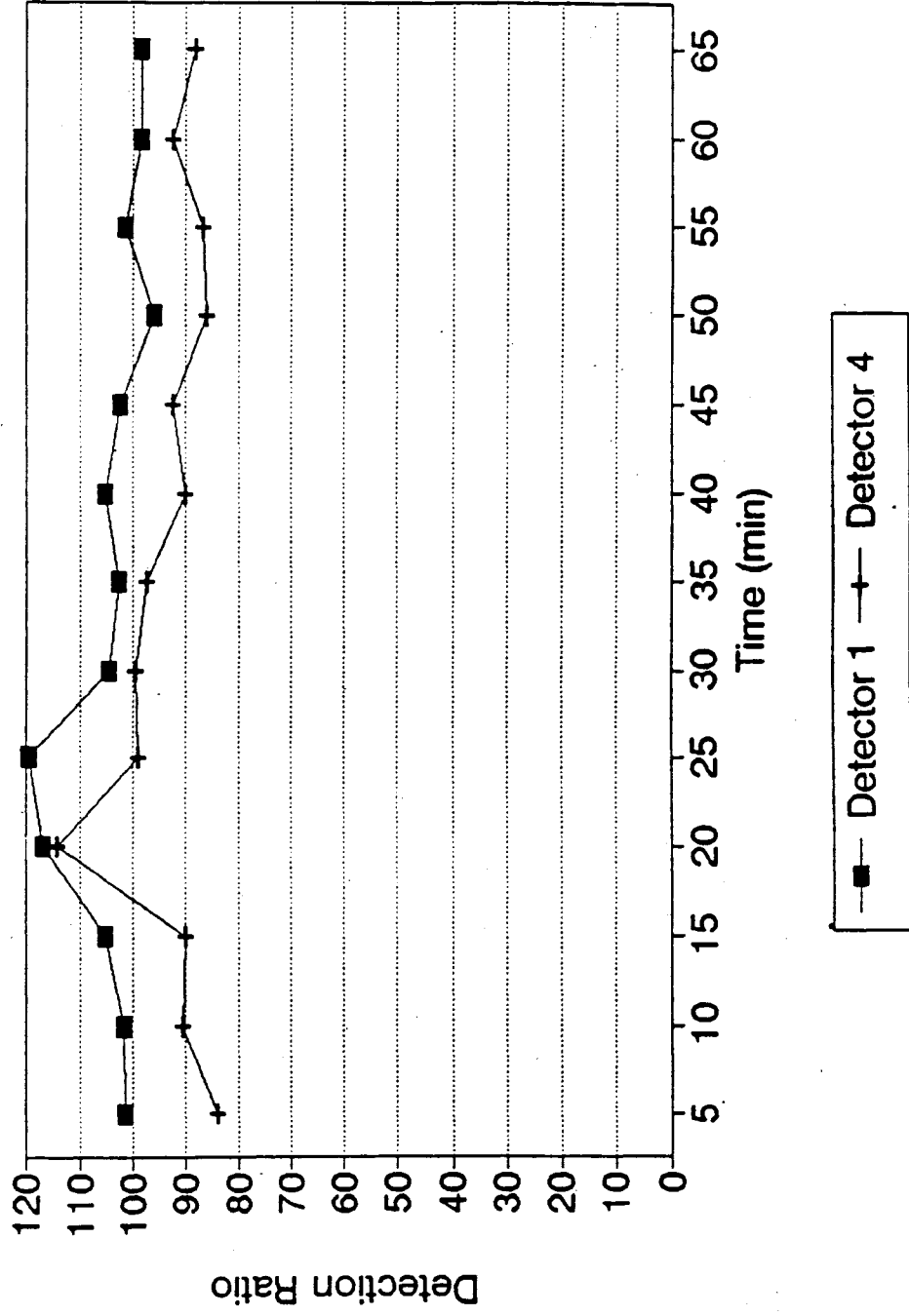


Figure 24
SMS Comparison Lyndale Tape Lane 2

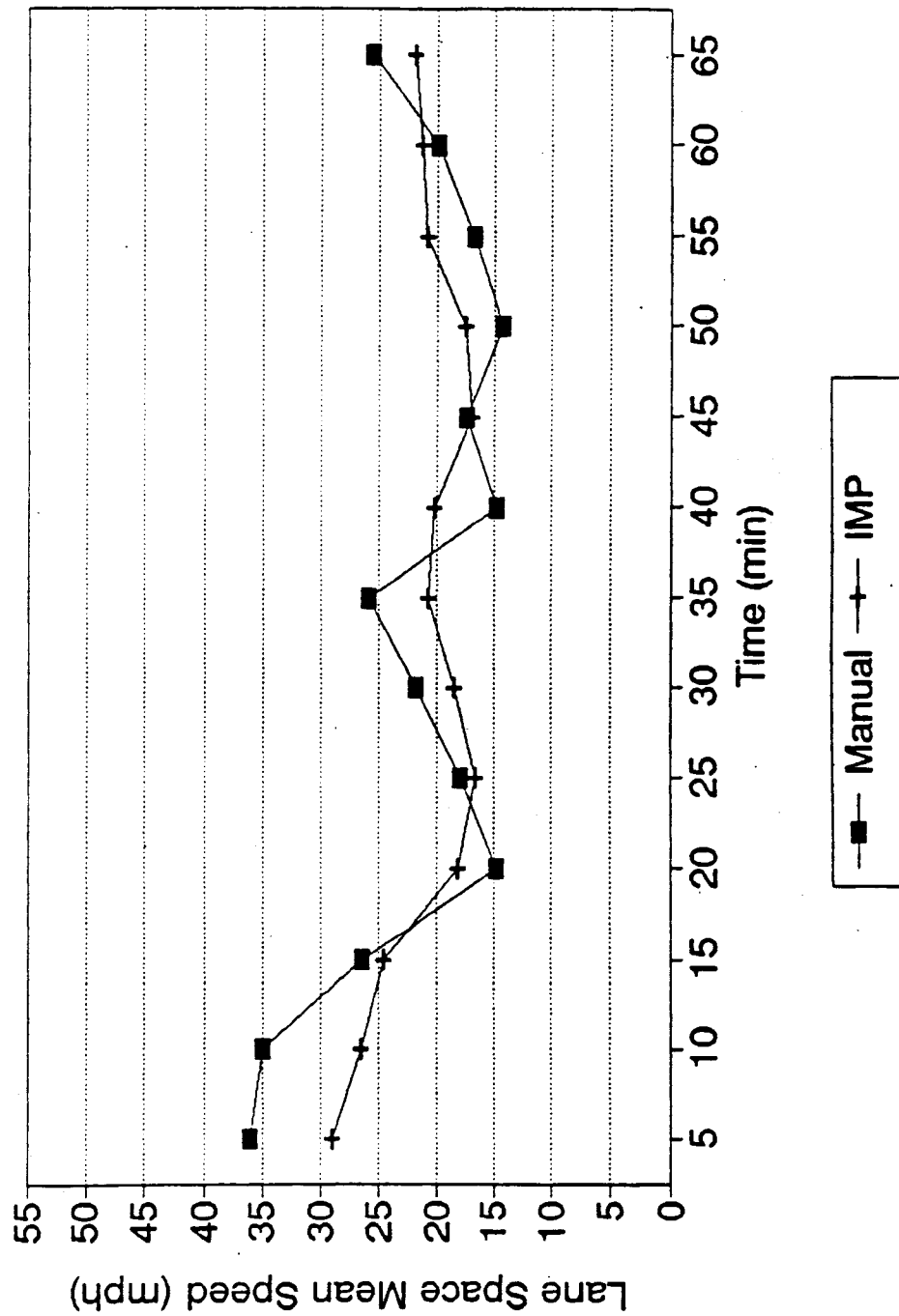


Figure 25
 TT Comparison Lyndale Tape Lane 2

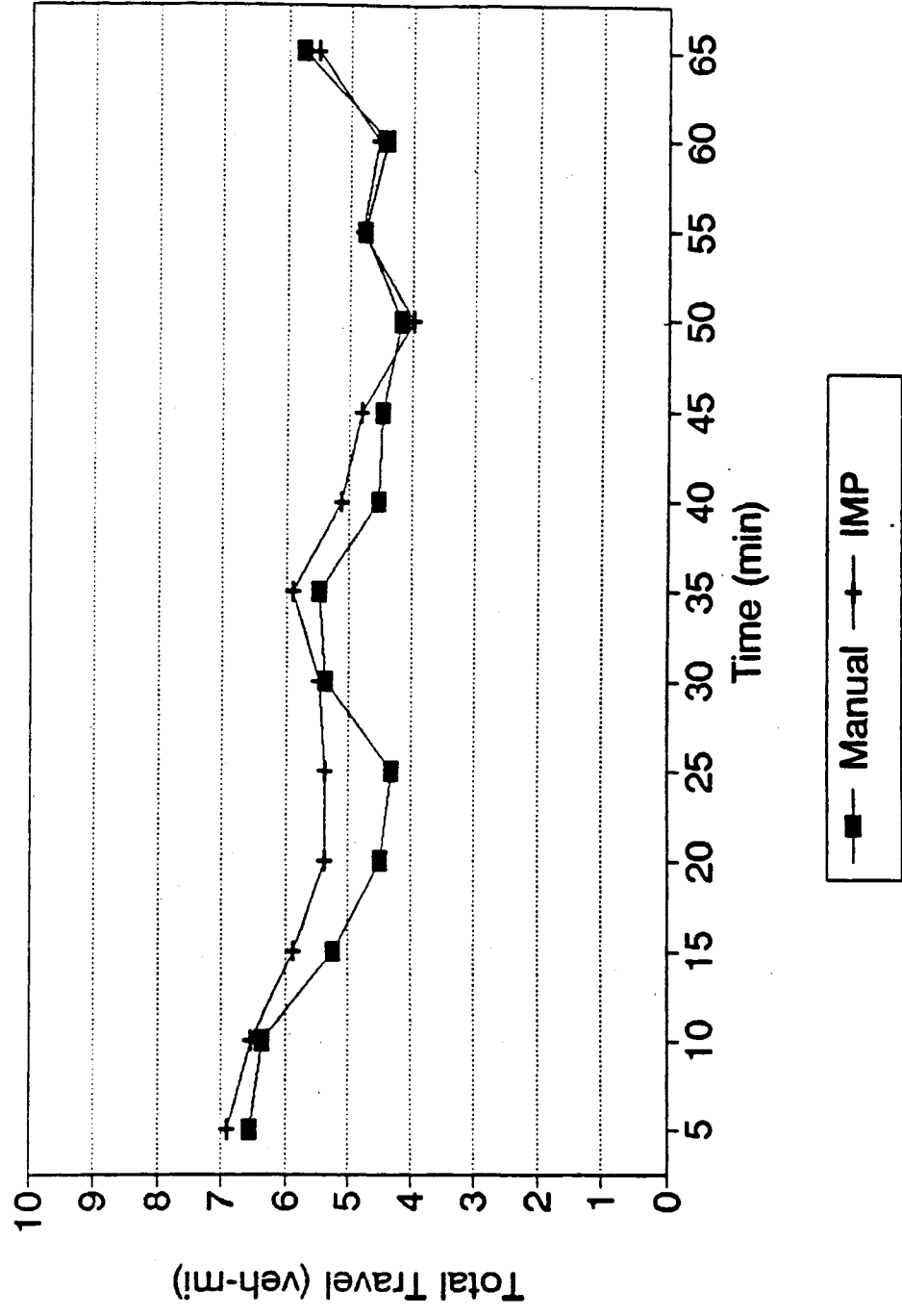


Figure 26

Delay Comparison Lyndale Tape Lane 2

