AN EVALUATION OF OPERATIONAL EFFECTS OF CORRIDOR-WIDE ACCESS-CONTROL MODIFICATIONS

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ABSTRACT

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High access densities and low corner clearances on multi-lane arterials with two-way left-turn lanes (TWLTL) have a significant detrimental effect on traffic safety and mobility. From the operational perspective, there is a wide range of criteria used by various agencies for the determination of corner clearances and access point densities. This research quantifies the operational impacts of access modifications at midblock and corner driveways on 5-lane roads with TWLTL using micro-simulation software VISSIM. The unique aspects of this research are that no major geometric changes in the corridor were made (other than signal optimization), and that modifications to corner and midblock driveways were also modeled simultaneously to evaluate their localized as well as combined effect on corridor-wide operations.

By varying mainline volumes, driveway volumes, access density, access location, and access type, 136 theoretical models were developed for urban arterials based on calibrated field conditions. The TWLTL operations in VISSIM were modeled by a combination of overlapping links and connectors. ‘Priority rules’ were used to determine the appropriate right-of-way for conflicting traffic using gap acceptance data for in- and out-bound driveway movements. It was determined that modeling TWLTL operations in VISSIM is only feasible for up to 24 midblock driveways per mile with up to 200 vehicles per hour per driveway (vphpd) so as to avoid overflow problem in the TWLTL with static routes.

The operational evaluation was performed at three levels using average delay (seconds/vehicle) as the primary measure of effectiveness (MOE): corridor-wide, signalized intersections, and driveway-specific. At the corridor-level, the average delay ranged from 50.9 s/veh for the model with five signalized intersections and no driveways with low mainline volume, to 94.7 s/veh for the model with five signalized intersection and 20 corner- and 24 midblock full-access driveways with high mainline volume. At the signalized intersections, the variation in average delays between cases was found to be small, with none of the intersections in any model shifting towards a better or worse level-of-service (LOS). However, direction-specific delays did have an impact on the driveway traffic especially at corner driveways. In the evaluation of driveways, the trends in increased delays were as expected, with increasing values as the number of driveways increased especially in full-access cases. It was found that that the impact of mainline volume is much more significant on driveway operations than the impact of increased driveway density. Also, the impact of driveway volumes was more pronounced at high mainline volumes. For low to medium mainline volumes, the increase in driveway volume did not have a significant impact on driveway delays.

The quantification of traffic operations from theoretical models is summarized in the form of flowcharts and corresponding case-specific results that will provide guidelines for transportation engineers and planners to determine the impact of various access management alternatives on urban arterials.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Access management strategies are devised to facilitate traffic mobility and improve safety by systematically controlling the spacing, location, design, and operation of driveways, medians and median openings, turn lanes, traffic signals, and interchanges *(1)*. In the functional hierarchy of roadways, primary and secondary arterials are perhaps the most critical corridors where poor access management can have a significant detrimental effect on traffic safety and mobility. In urban and suburban areas, arterials comprise anywhere from 20 to 35 percent of the total roadway miles, providing direct access to major traffic generators *(2)*. Application of access management principles can address potential traffic problems for future developments along the roads by limiting the number of direct access points, locating driveways farther from the influence of intersections, and using non-traversable medians. In this context, existing arterials with two-way left-turn lanes (TWLTL), high access-densities, and low corner-clearances pose a special challenge for transportation engineers from operational, legal, and economic perspectives.

Left turns in and out of driveways are generally the most problematic movements on high volume urban and suburban arterials with a disproportionately high number of access points to adjacent developments and/or inadequate corner clearances. Theoretically, the treatment alternatives to mitigate the operational and safety problems without changing the characteristics of the arterial itself (e.g., replacing TWLTL with medians) are limited to driveway closure, relocation, consolidation, or movement restrictions on driveways. These treatments generally have a positive impact on the operations and safety of a corridor by reducing the number of conflicts points and improvements in traffic flow. However, in many situations it is a daunting task for an agency to require existing developments to remove or alter driveways that hinder traffic operations and/or create safety problems.

Researchers have extensively dealt with the topics of inadequate corner clearances and high access densities from the perspective of traffic safety. One of the most common recommendations found in the literature is to eliminate all left turns from driveways by installing a raised median with median breaks that allows downstream U-turns at controlled locations and subsequent right turns into developments. However, changing the character of an entire arterial by removing the TWLTL and providing a continuous median with breaks for left turns in order to facilitate access for a few problematic driveways is seldom economically feasible.

The guidelines provided in national and state references and handbooks address the issues of corner clearance and access density primarily for future developments. These guidelines provide a wide range of criteria for the determination of adequate corner clearances and access point densities including type of roadway, average daily traffic, and speed limit. Given that, there is a wide range of recommended values for specific roadway types between various state and national manuals. For existing multilane urban arterials with TWLTL or other configurations (e.g., four-lane sections) that violate the prevailing minimum corner clearance and access point density criteria, the literature provides very few quantitative guidelines for reducing access problems. This is due in part to the analytical challenges associated with the study of corridors with a TWLTL in real-world situations as well as in simulation environments.

Current thrusts in access management research and practice are to address many important issues broadly rather than employing rigorous engineering analyses of operational problems. These include: economic impacts of implementing various access management techniques; improvements in overall mobility by coordinating different modes of transport; coordination between intergovernmental agencies for uniform access management; development of performance measures of access management strategies; effectiveness of access management in traffic incidents and emergency response; and development of access management guidelines for future applications.

In this context, this research is focused on the quantification of operational impacts of access modifications at midblock driveway locations and within the functional areas of signalized intersections on multilane roadways with a TWLTL. The effects of these modifications are studied at the level of individual driveways and intersections, as well as at the corridor level utilizing microscopic traffic simulation software. The unique aspects of this research are that no major geometric changes to the corridor itself are made, and that modifications to corner and midblock driveways are modeled simultaneously to evaluate their combined effect on traffic operations. The overall objective of the research is to develop guidelines for transportation practitioners, which provide thresholds for operational parameters that may be utilized to indicate the need to modify corner clearance and/or access density on an arterial roadway.

This dissertation is organized as follows.

- The next chapter is a primer on the state of practice on the issues of access density and corner clearance. Also, a critical review of recent research on these specific topics is presented.

- Chapter 3 includes the description of the problem, objectives and scope of the research, and the general approach taken in the study.
- Chapter 4 is a description of the evaluation of the base model including description of the site, data collection efforts, assumptions and limitation of the traffic simulation, model calibration and validation, and modeling of the TWLTL.
- Treatment alternatives and the development of theoretical models are presented in chapter 5. Measures of effectiveness (MOE) are defined, and the simulation modeling methodology is presented.
- In chapter 6, evaluation and results from the theoretical modeling are presented along with the analysis of MOEs of treatment alternatives. General guidelines for practitioners are presented for the location, spacing, and control of corner and midblock driveways based on operational impacts at various levels including driveways, adjacent intersections, and the overall corridor.
- Chapter 7 is a compilation of the key outcomes of this research, and recommendations for future work on the development of consistent criteria for mitigating access problems on existing multilane roads with a TWLTL.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Access management issues have been researched extensively by various federal, state and local transportation agencies. Given the practical nature of the problem of determining optimal location of access points on a roadway, most states have devised guidelines for access location, spacing, and design. The objective of this literature review is to study the quantitative and qualitative guidelines used in practice, and to summarize relevant research on the operational impact of various access management configurations. The literature review is presented in three parts. First, references used at the national level, including those developed by the Transportation Research Board (TRB), National Cooperative Highway Research Program (NCHRP), American Association of State Highway and Transportation Officials (AASHTO) and Institute of Transportation Engineers (ITE) are reviewed. Then, a review of recent publications on operational impacts of access restrictions is presented. Finally, a review of practice is presented, which includes a summary of access control policies from various states. Note that this literature review is an update of the material presented in '*An Evaluation of Right-Turn-In/Right-Turn-Out Restrictions in Access Management'* by Lyles et al *(3)*.

2.2 Review of National Guidelines and Resources

TRB's *Access Management Manual (1)* is a compilation of state-of-the-art access management techniques, whose purpose is to provide guidance to all levels of transportation agencies as well as consultants in developing and implementing access management programs.

The manual provides detailed technical information on several elements of access management including: basic concepts of access management; development of local, regional, and corridor access management programs; access categories; land development; access location, spacing and design; median treatments; permits, right-of-way and legal matters; agency coordination; and public involvement in the access management process. A brief summary of the elements related to access restrictions near signalized intersection and mid-block driveways on urban/suburban arterials is provided.

Access management techniques have an impact on traffic operations, roadway safety, economics, and the environment. According to the TRB manual *(1)*, increasing the design speed of the entry or exit maneuver at a driveway from 5 miles per hour (mph) to 10 mph results in 50% reduction in delay per maneuver. Visual cues at driveways including illumination have been shown to reduce crashes by 42%. The manual also reports that business owners perceive the economic impact of changes in property access to be much worse than they actually are.

Design considerations for a driveway include turning radius, width, number of lanes, throat length, auxiliary turn lanes and directional controls *(1).* The manual recommends avoiding locating the driveways in intersection acceleration/deceleration lanes and tapers to minimize weaving conflicts. A few examples are also provided of states and local agencies that have specific provisions prohibiting this practice.

Spacing for unsignalized access points must be determined using the following criteria: safety, stopping sight distance, intersection sight distance, functional area, right turn conflict overlap, influence distance, and egress capacity *(1).* The manual presents numerical details on the aforementioned criteria for various traffic and roadway configurations. In terms of corner clearance, the manual provides sample clearance criteria for upstream and downstream driveways for both major and minor roadways. These criteria are based on the functional area of the intersection, stopping distance, and the effect of queuing from the intersection.

The manual provides comparisons of midblock left-turn treatment types including non-traversable medians, TWLTLs, and undivided cross-sections. Comparisons are made in terms of operational effects, safety effects, aesthetics, snow removal, and construction cost. To that end, undivided cross-sections were found to be least effective/desirable. Comparison of operational effects including delays and capacity indicate no significant difference between non-traversable medians and TWLTL. Non-traversable medians were found to be more effective than TWLTL in reducing vehicular crashes.

While the *Access Management Manual (1)* provides useful insights into access restriction studies, it does not provide quantitative thresholds for access restrictions along urban/suburban arterials with center turn lanes where significantly altering the median is not an option.

A Policy on Geometric Design of Highway and Streets (2) by AASHTO provides definitions of physical and functional areas of an intersection. The three basic elements for defining the functional area of an intersection/driveway approach are: perception-reaction distance; maneuver distance; and queue-storage distance. It is stipulated that under ideal conditions, driveways should not be located within the functional area of an intersection, or within the influence area of an adjacent driveway. The influence area of a driveway includes: the impact length, defined as the distance back from a driveway where cars begin to be affected; the perception-reaction distance; and the car length. Impact lengths related to vehicles making right turns into driveways are also provided. These range from 245-ft at 20 mph to 725-ft at 55 mph.

NCHRP Report 93*, Guidelines for Medial and Marginal Access Control on Major Roadways (4)*, states that TWLTLs are useful treatments when driveway volumes are relatively low, however, TWLTLs on new arterials should not be used and development patterns should be adopted that will reduce frequent direct access points. A before-after study done in Texas to evaluate the loss of business due to elimination of left turns using a median indicated a 59 percent reduction in left- and U-turn movements, as well as a 23 percent reduction in right turns in the ‘after’ period. An evaluation of the economic effects indicated that a positive correlation exists between percentage losses in sales and percentage losses in left turns. The report provides some guidance for the distance required for entering a multilane arterial from a corner driveway as a function of through volume. Also, the percentage of cycles when a driveway close to an intersection will be blocked is tabulated as a function of flow in the lane adjacent to the driveway and duration of the red phase. In cases of limited corner clearance, the probability that egress will be blocked increases significantly when the adjacent lane approaches the lane capacity of the intersection.

Unsignalized driveway access spacing is usually determined with consideration of weaving and merging distances, stopping sight distance, acceleration rates, and storage area in the TWLTL for closely-spaced driveways. According to NCHRP Report 348, *Access Management Guidelines for Activity Centers (5)*, unsignalized driveways should be treated like public streets for the purpose of spacing, resulting in a minimum spacing of 500-ft, which is far less than acceptable limits of 100-ft to 200-ft typically required from an economic development standpoint. In this context, guidelines for access spacing based on operating speed, access level, corner clearance, and the size of generator are presented. Also, some guidance in terms of access restrictions is provided. For example, given a speed and access classification for a roadway, whether a traffic generator (minor or major) should have right-turn-only access, or be allowed left turn access (if signal spacing requirements are fulfilled).

The NCHRP Report 348 *(5)* also recommends closing or relocating poorly spaced driveways. It suggests that driveways located within 100-ft of an intersection be considered for closure. Also, driveways within the normal queuing distance of signalized intersections should be removed, moved farther from the intersection, or restricted to right turns only. In terms of economic impacts of TWLTLs and raised medians, the report summarizes studies done in Texas and Georgia, where researchers found no overall negative impact of replacing TWLTL with raised medians.

The Transportation Research Circular (TRC) 465, *Driveway and Street Intersection Spacing (6)*, provides some additional parameters [in addition to ref. *(5)*] for the spacing of driveways. These include: location of upstream and downstream driveways, volume of trucks, expectancy of drivers, separation of conflict areas, and egress capacity.

A comprehensive study for evaluation of alternative midblock left turn treatments including raised-curb median, flush median with TWLTL delineation, and undivided cross-section on urban and suburban arterials is presented in the NCHRP Report 395, *Capacity and Operational Effects of Midblock Left-Turn Lanes (7)*. Road user benefits for alternative treatments were computed from the performance measures, which were derived from operations and safety models. A comparison of these benefits was made with the construction cost of treatment conversion to determine financial feasibility of alternatives. The authors concluded that motorists experience similar delays on arterials with raised-curb median compared to arterials with TWLTL for a wide range of traffic and geometric conditions. Accidents on street segments were more pronounced for cases where traffic demand was higher, and also where driveway and public street densities were higher. The report suggests that businesses that provide reliable and quality services would be able to overcome reductions in property access volume.

NCHRP Report 420, *Impacts of Access Management Techniques (8)*, provides qualitative guidelines to establish corner clearance criteria. The report suggests that near- and far-side corner clearance criteria be examined independently. The principles provided to determine corner clearance and retrofit measures for existing driveways include: a restrictive median to prohibit left turns onto major highways; only one driveway per road per corner parcel placed at the farthest possible distance from the intersection; eliminating all left turns at driveways within the "influence area" *(8)* of an intersection using short median dividers and/or modified driveway design; consolidating driveways with adjacent properties; and eliminating driveways and providing property access from secondary roads.

NCHRP Report 504, *Design Speed, Operating Speed, and Posted Speed Practices (9)*, indicates that access density and median type influence the 85th percentile free-flow speed on tangent road segments. Based on field studies on a range of access densities along local, collector, and arterial streets, this research concluded a strong linear relationship with higher speeds at lower access density roadway segments. Regression models based on this relationship were also developed for posted speed limits between 30 and 50 miles per hour.

NCHRP Report 659, *Guide for the Geometric Design of Driveways (10)*, provides general guidelines for driveway location and spacing on arterials and near interchanges. This report summarizes recommendations made by AASHTO *(2)* and other NCHRP reports (reviewed earlier) and does not provide additional or specific quantitative variables for restricting access from operation or safety perspectives.

Numerical procedures to compute the minimum corner clearance are provided in NCHRP Synthesis 299, *Recent Geometric Design Research for Improved Safety and Operations (11)*. These models originally developed by Long and Gan *(12)* are based on computing minimum corner clearance under either saturated flow or unsaturated flow conditions, multiplied by adjustment factors for facility type, median type, driveway traffic and geometric features, and traffic stream characteristics.

NCHRP Synthesis 304, *Driveway Regulation Practices (13)*, documents the driveway regulation practices of several state and local agencies. Based on a survey conducted by the researchers, it was found that only a few agencies have separate permitting procedures for new developments and redevelopment of existing driveways. It was also revealed that almost all transportation agencies face difficulties in forcing driveway retrofit treatments. Although consolidation of driveways and shared access are encouraged by a majority of state and local agencies, these have been achieved successfully only through coordination of local governments and cooperation by property owners.

One of the most common recommendations found in any access management document is to eliminate all left turns from driveways by installing raised median with median breaks that allow downstream U-turns at controlled locations and subsequent right turns into developments. In that context, where such recommendations are feasible given the arterial classification and cost considerations, the safety of U-turns at unsignalized median openings is of concern. The guidelines for the use, location, and design of unsignalized median openings, and their safety performance on urban/suburban arterials are presented in NCHRP Report 524, *Safety of U-Turns at Unsignalized Median Openings (14).* This report is based on field studies of driver behavior at median openings. The researchers found no indication of unsignalized median openings being a major safety concern for urban arterial corridors. These studies support access management strategies that increase U-turn volumes at unsignalized median openings.

The NCHRP Synthesis 332, *Access Management on Crossroads in the Vicinity of Interchanges (15)*, summarizes state practices related to access location and design on crossroads in the vicinity of interchanges. According to a survey conducted to document state practices, 27 states indicated having guidelines for spacing of driveways on interchange crossroads. The minimum spacing standard used by the Michigan Department of Transportation (MDOT) in this case is 100-ft. In addition to the factors used for arterials, other variables that influence access location spacing on interchange crossroads include: interchange form; type of downstream access point; cost and economic impacts; and level of interchange importance.

NCHRP Synthesis 337, *Cooperative Agreements for Corridor Management (16)*, provides best practices to formalize cooperation between government and private entities for the purpose of strengthening the linkage between land use and transportation facilities. Survey results (for practice in the U.S.) indicated that agreements pertaining to access management that are not typically bound to specific projects have no limits in terms of time duration. The biggest issues in developing and implementing cooperative agreements as indicated by the respondents included: lack of understanding of corridor management and consequently local and public opposition; lack of leadership; lack of adherence to commitments by local agencies; and, need for technical assistance. The synthesis emphasizes the importance of a shared common vision for the corridors by all parties involved in such agreements.

To assure the safety, mobility, and economic benefits of access management, integration of best access management practices into the transportation planning process is vital and can be achieved through cooperation and coordination of different government units. In this context, the NCHRP Report 548, *A Guidebook for Including Access Management in Transportation Planning (17)*, provides guidance for addressing access management and related implementation mechanisms. Guidance is provided in the following planning areas: overall planning process, policy and system planning, corridor and subarea planning, and implementation through MPOs and local governments. NCHRP Report 661, *A Guidebook for Corridor-Based Statewide Transportation Planning (18)*, suggests a framework for conducting corridor level studies; however the emphasis is on investment and non-investment strategies rather than engineering analysis.

The ITE *Transportation and Land Development (19)* handbook provides detailed methodologies for the design of driveways, and also provides some guidance in determining minimum corner clearance based on queue lengths that will potentially block the access. However, these guidelines developed in 1970 need to be updated since signalized intersections have significantly evolved with time.

2.3 Review of State of the Art

This section is a review of the state of the art on operational studies conducted in the context of access management, specifically for the study of turn restrictions at corner and mid-block driveways, simulation modeling of access management alternatives, and the development of performance measures for driveways and corridors.

Access management alternatives were studied using VISSIM simulation software by Dale and Woody *(20)* to explore issues related to the modeling of TWLTL operations and safety, median operations, truck backing, and on- and off-street parking. TWLTL modeling alternatives are presented for low- and high-turning volumes using the ‘priority rule’ configuration in VISSIM which allows the assignment of appropriate right-of-ways to potentially conflicting traffic *(21)*. This research also provides qualitative guidelines on the utility of the VISSIM simulation software for the purposes of visualization and analysis. The researchers suggest that given the amount of effort required for complex modeling of TWLTL, the relative utility for analytical purposes is low even in low turning volume situations.

A 'Corridor Visualization Explorer' *(22)* tool developed for the Louisiana Department of Transportation and Development provides planning level estimates of corridor performance for various roadway configurations including two- and four-lane undivided, 6-lane divided, and 4-lane with TWLTL. Also, a range of driveway and signalized intersection densities may be selected to get overall estimates for delay per vehicle, multi-modal quality of service, potential for crashes, and economic impact. However, quantitative operational variables produced for different scenarios are not based on specific field or simulation studies. It is noted that the utility of the tool is primarily for the communication of access management principles rather than determining operational thresholds for access restriction alternatives.

Malik et al. *(23)* performed simulation modeling of corner and mid-block driveways in VISSIM using field data in Michigan to determine the impact of through volume on movement-specific driveway delays. This research recommended that left-turn in/out movements on 5-lane sections should be restricted if the corner clearance is less than 100-ft and the mainline volume is greater than 500 vehicles per hour. Also, left-turn restrictions should be considered for mid-block locations where mainline volume exceeds 1500 vehicles per hour.

Prassas and Chang *(24)* studied the effects of arterial demand volume, driveway volume, and interaction between multiple full-access midblock driveways on a 4-lane arterial with median and median breaks using the simulation package CORSIM. The MOEs used in their study included average speed of through vehicles on the arterial, driveway delay, and queuing. Complex interactions between driveways due to "de-structuring" and re-structuring of platoons were studied, and capacity reduction at downstream driveways were estimated to be in the range of 30-50 percent due to the presence of upstream driveways.

A simulation study was conducted by Zhou et al. *(25)* to evaluate the effect of change in access point spacing near a freeway interchange in Florida. The operational effects were measured in terms of queue length on the off ramp and network delay. It was found that increasing the spacing of the first access point from the off ramp from 200-ft to 600-ft significantly reduced the off ramp queues and overall network delay. The positive effects of access spacing appeared to level-off after 600-ft (modeled up to 1320-ft).

Gluck et al. *(26)* presented a comparison of theoretical versus practical alternatives to address access management problems for a highway in a densely developed, commercial area in New York. The accident rate for this road was 47% higher than the statewide average rate, with oversaturated conditions, recurrent congestion, heavy turning movement volumes, overlapping conflicts, and numerous weaving movements. A less viable (albeit cheaper) solution was selected by the implementing agency as opposed to the preferred alternative that included major geometric changes and potentially significant reduction in crashes mainly due to: increased pedestrian crossing distance; change in character and aesthetics of the highway; access modifications at major shopping centers; changes in internal circulation of businesses and reduced parking; and potential rerouting of school buses.

Jacobson et al. *(27)* conducted research on access spacing for non-freeway weaving situations in Texas using field studies, CORSIM simulation, and linear regression. Safety and operational analyses were performed for frontage roads with various unsignalized access spacing (between exit ramp and driveways) to develop level of service (LOS) criteria for frontage roads. The regression model for safety evaluation revealed that posted speed limit, number of through lanes, and existence of nearby downstream entrance ramp had a significant effect on the total accident rate on the frontage road. Also, the accident rates were highest for cases where spacing was less than 150 m (500 ft). For operational analysis, density was used as an MOE and regression models were developed for various geometric configurations. The total weaving section volume, driveway volume, and exit ramp to driveway or street spacing were found to be statistically significant in predicting the length of the weaving section on the frontage roads. The regression equations were then solved to determine minimum spacing required to maintain the desired level of density for a given volume.

Gan and Long *(28)* provide a synthesis of the effects of insufficient corner clearance on traffic operations, safety, and capacity. Operational problems that arise due to inadequate corner clearance include: blockage of driveway egress movement; blockage of driveway ingress movement; incomplete turning maneuver; conflicts with intersection turning movements; dual interpretation of right-turn signals; merging bay vehicular conflicts and reduced merging length; insufficient weaving section length; and emerging vehicular conflicts from driveways on right-turn bays. The researchers note that the safety impact due to inadequate corner clearance is complicated by insufficient level of details in crash databases. The researchers also developed a model to determine minimum corner clearance at signalized intersections *(28)*. The following shortcomings in various states' guidelines in determination of minimum corner clearance were revealed: lack of consideration of driveway impacts on intersection capacity; incorporation of a limited number of driveway design features; little consensus on factors to determine corner clearance; and arbitrary grouping of variables such as the size of traffic generators.

The model for minimum corner clearance at signalized intersections proposed by Gan and Long *(28)* is structured similar to the Highway Capacity Manual's (HCM) model for saturation flow rate. In this case, first an initial minimum corner clearance is calculated for either saturated or unsaturated flow conditions, and then adjustment factors are applied for facility type, median type, driveway channelization, driveway width, driveway traffic volume, peak-hour driveway heavy-vehicle volume, coincidence of driveway and arterial peak-period volumes, driveway corner turning speed, and curb lane width. These adjustment factors were derived from existing guidelines but not calibrated using statistical methods or field studies.

Gluck et al. *(29)* conducted field studies at 22 sites in four states to quantify the effects of right-turning vehicles into driveways on other vehicles following in the same (right) lane. In the field, these effects were measured by indication of brake lights and/or evasive maneuvers taken by following through vehicles. Data gathered for single driveways were expanded statistically for multiple driveways and impact lengths were calculated. The study provided various ranges of right-turning volumes and corresponding percentages of affected through vehicles as well as driveway influence lengths.

Simulation studies based on field data from Texas and Oklahoma as well as theoretical corridors were conducted using VISSIM by Eisele and Frawley *(30)* to estimate the safety and operational impacts of raised medians and driveway density. Travel time, speed, delay, and accident rates were computed for various access densities and the presence of raised medians and/or TWLTL. Replacing TWLTL with raised medians resulted in an increase in travel time in the majority of cases, and the reduction in the number of vehicular conflict points resulted in increased safety as determined by the before/after crash analysis for study corridors. The research also showed that crash rate increases with the increase in driveway density, regardless of the type of median.

Regression models were developed by Zhou et al. *(31)* to predict delays and travel times for direct left turns and for U-turns followed by right turns from unsignalized driveways. The delay model for direct left turn predicts average total delay from the flow rate of major road through traffic, percentage of upstream through traffic, flow rate of left-turn-in traffic from a major roadway, and flow rate of direct left turn. The delay model for a right turn followed by U-turn predicts average total delay based on the two-directional flow rate of major road, flow rate of the right turn followed by U-turn, and percentage of upstream through traffic. The average travel time of direct left turns is predicted from flow rate of major road through traffic, flow rate of direct left turn, flow rate of left-turn-in traffic, and percentage of upstream through traffic. The average total travel time of U-turns followed by right turns is predicted using two-directional flow rate of major road, flow rate of right turn followed by U-turn, percentage of upstream through traffic flow rate, and speed.

The effects of U-turns on the left turn saturation flow rate at signalized intersections were quantified by Carter et al. *(32)* using field data from North Carolina. They developed a regression equation for the adjustment factor for U-turns in an exclusive left turn lane with protected phasing, which depends upon the average U-turn percentage in the exclusive left turn lane, and whether or not the conflicting right turn has protected overlap. They concluded that for every 10% increase in the average U-turn percentage, there was a saturation flow rate loss of 1.8%. For protected right turn overlap from the cross street, there was an additional 1.5% saturation flow rate loss per 10% increase in the number of U-turns.

The review of recent literature on the impacts of access management techniques indicates a focus on the safety aspects and limited research on the operational evaluation. In studies that address the operational aspects of access management, the analysis is limited to site-specific issues and potential solutions. An area where operational impacts are studied the most is the conversion of undivided highway to divided highways and by adding midblock U-turns for left-in movements. The literature review indicates a need for quantification of the impacts of driveway location and spacing on undivided highways in a systematic fashion to study the variation in system-wide as well as localized MOEs with varying levels of traffic volumes without changing the geometric characteristics of the road.

2.4 Review of Practice

Access management documents (including manuals and other publications) for several states were reviewed to identify standards, guidelines, or rules for allowing or restricting turning movements at driveways. For example, when to provide them and when to restrict them, how they are controlled, and what the design standards are for driveway width, spacing and corner clearance. In this review of material available on-line at states' websites, information was found for 33 states. Most of these states have provided statutes and design standards for driveways but only a few have implemented a formal turn restriction policy at driveways. The findings for various states are summarized as follows. Note that state-specific statutes pertaining to driveway permits are not included in this review.

Chowdhury et al. *(33)* conducted a survey of state transportation agencies to assess the practice of left-turn restrictions from driveways and alternative treatments to direct left turns. Based on the responses from 25 agencies, the researchers concluded that there was a lack of such standards for most states, and that most agencies address these issues on a case-by-case basis. Different states use different factors to determine left-turn restrictions from driveways including:

traffic volumes, crash experience, type of through road, distance from adjacent median opening, access point density, speed limit, and average daily traffic.

Arizona *(34)* is currently (2011) developing a statewide access management plan in consideration of the unprecedented growth in population and transportation infrastructure. Among other elements, this plan will include access type, location, and design criteria for individual driveways as well as corridor-wide and interchange-area access management components. Note that while a statewide plan is in development, local agencies (counties and cities) have used a number of different criteria to determine access location and spacing for new developments over the years.

Colorado *(35)* suggests restricting certain turning movements at driveways by channelized islands if the driveway volume is predicted to exceed 100 DHV (design hourly volume). Left turns are allowed on an undivided highway by the approval of the permitting authority.

Delaware *(36)* and **Kansas** *(37)* do not address when to provide right-in/out only driveways but recommend proper channelization to control these types of driveways. **Delaware** allows left turns where design meets all safety requirements. It also recommends median crossover and channelization to control for both right and left turns. **Kansas** also suggests modifications in median crossovers to accommodate projected traffic movements.

Seven states including **Florida** *(38)***, Idaho** *(39)***, Kentucky** *(40)***, North Carolina** *(41)***,** **Texas** *(42)***, Utah** *(43)* and **Virginia** *(44)* have similar guidelines for right-in/out only driveways. When sufficient corner clearance cannot be met or if access connections have to be located within the functional area due to limited property frontage, the access may be restricted to right-in/out only or other limited movement treatments. **Texas** addresses this issue along with connection spacing. According to **Texas** guidelines, it is also important to maintain adequate connection spacing, and if it cannot be achieved then lesser spacing for a shared access with an abutting property may be allowed. In case of no other alternatives, **Texas** allows access along the property line farthest from the intersection but to ensure safety under these conditions, it recommends allowing only right-in/out turning movements if feasible.

Florida has the most extensive set of documents *(38)* providing guidelines on all aspects of access management. In terms of access restrictions, Florida has moved from driveway-specific criteria to corridor preservation techniques that take a broader approach to balance access and mobility. This approach, however, is mostly supported by recommendations based on crash experience rather than extensive operational evaluation of corridor-wide access control modifications.

Driveway spacing guidelines in **Georgia** *(45)* suggest that the driveway spacing should at least be equal to the distance traveled during the normal perception reaction time at the posted speed plus the distance traveled as the vehicle decelerates to a stop. Minimum driveway spacing distances ranging from 125-ft to 550-ft are provided for posted speed limits from 25 to 65 miles per hour, respectively.

Idaho *(39)* provides a general policy statement regarding access control which shall be based on the highway functional classification. Spacing distances for signals, intersections, approaches and frontage roads are provided separately for urban and rural highways.

According to **Indiana** *(46)*, major driveways into developments such as shopping centers should be constructed so that there is no conflict between the inbound/outbound vehicles and the cross traffic movements within 100-ft of the driveway entrance. This may be accomplished by the use of a raised island. In the context of left turns, the state guidelines recommend dedicated left turn lanes for the driveway and left-turn deceleration lanes on the highways to achieve a required level of service above “C”. For high-volume traffic generators such as shopping centers, industrial plants, industrial parks, residential projects, and similar developments, a median crossover is desirable.

Iowa *(47)* suggests that a median opening should not be permitted except to accommodate large traffic-generating facilities such as large shopping centers or industrial plants. Median openings may be permitted in these instances if adequately justified to account for turning movements.

For arterial and collector roads, **Louisiana** *(48)* suggests ‘desirable’ connection spacing of 550-ft and 300-ft respectively. For local roads, the access connections are recommended to be located such as to achieve the greatest possible spacing within property constraints.

Maryland *(49)* recommends using right-in/right-out driveways on all divided highways with posted speeds above 40 mph. In urban street environments where posted speeds are 40 mph or lower and a narrow median separates the directional highways, it allows the use of right-in/out driveways as long as appropriate signing is provided to discourage errant movements.

Missouri *(50)* provides guidelines for use of TWLTL for urban areas and prohibits use of TWLTL in rural areas. For urban principal and minor arterials, TWLTL is permitted if Annual Average Daily Traffic (AADT) is less than 28,000 in the design year for 5-lane sections, and if AADT is less than 17,500 for 3-lane sections. The minimum driveway spacing guidelines for urban areas range from 220-ft on collectors to 660-ft on principal arterials.

Minnesota *(51)* addresses access on existing roadways and recommends limiting the entrance to right-in/right-out only, unless weaving or other traffic operations indicate the need for further restrictions on turning movements (e.g. right-in only or right-out only). It also suggests limiting the access to right-in/right-out movements on planned highways where a median is to be constructed.

Nebraska's *(52)* guidelines on access spacing consists of general statements regarding efforts to consolidate access locations, for example in developed urban areas the access locations should be no closer than two blocks.

Non-signalized driveway spacing requirements in **Nevada** *(53)* are based on 85^{th} percentile speed, which provide a range of spacing from 100-ft to 1200-ft for respective speeds from 25 miles per hour to 70 miles per hour.

New Jersey *(54)* provides two scenarios to restrict left turns: if future traffic volumes warrant installing a traffic signal and signalized spacing requirements cannot be met, a left-turn access may be closed; and, if an undivided highway becomes divided as a condition of the access permit, left turn-access may be closed. In both cases, access should be closed for left turns in accordance with the standards provided by the New Jersey Access Management Code.

New Mexico *(55)* suggests restrictions to full access when there are issues related to safety or operational deficiencies (high crash rate and/or decreased LOS) that would be expected if a full access median was implemented. Geometric design and channelization should be used to restrict undesirable movements.

Oregon *(56)* extensively utilizes the concept of 'functional intersection area' *(29)* to compute stopping and decision sight distances to determine access spacing for various roadway types under varying speeds.

According to **Ohio** *(57)*, left turn movements shall not be permitted if a median is already established and the opening of the median would not provide, in the determination of the department, any ‘significant’ (undefined) operational or safety benefits to the general public or would be counter to the purpose of the median construction.

Pennsylvania *(58)* implements turn restrictions if the improvements that would be required at a driveway to achieve acceptable levels of service cannot be provided due to constraints, or if there is a history of high crash rates due to left-turning vehicles. For high and medium volume driveways, channelization islands and medians shall be used to separate conflicting traffic movements into specified lanes to facilitate orderly movements for vehicles and pedestrians.

South Carolina *(59)* uses a minimum corner clearance of 125-ft at stop-controlled intersections, and 150-ft at signalized intersections. The driveway spacing criteria used are posted speed limits and ADT.

Vermont *(60)* permits one or both left turn movements at the access point if the applicant establishes to the agency's satisfaction that left turn movements would not create unreasonable congestion or safety problems, or lower the level of service below agency policy.

In **Washington** *(61)*, all private access connections are for right turns only on multi-lane facilities unless there are special conditions and the exception can be justified.

Wyoming *(62)* recommends installing a median island on multi-lane urban arterials if the average daily traffic (ADT) is more than 30,000. In this case, direct accesses would be right-in/right-out only and they should be provided with right turn deceleration lanes.

Several states including **Georgia, Maine, Michigan, West Virginia** and **South Dakota** describe generally that raised islands or channelization is an effective practice to control right-in/out-only driveways. On the other hand, left turns can be accommodated with proper median opening design. **Maine** also suggests two-way-left-turn-lanes onto a ‘mobility arterial’ to accommodate left turns. A ‘mobility arterial’ is defined by **Maine** as an arterial corridor located in ‘Urban Compact Areas’ that carries an AADT of at least 5,000 vehicles per day for at least 50% of its length and with speed limit of 40 mph or more.

From the review of state practices, it can be concluded that there is not a consistent set of criteria followed by all or most states related to corner clearance and mid-block turning restrictions in their access management policies. Most of the states which address this issue provide criteria to restrict turning movements, which include level of service, average daily traffic, and crash history. Even in those cases, only generic statements are provided rather than quantitative thresholds for restrictions. A few states recommend providing right-in/out only driveways when there is insufficient corner clearance and there is no other alternative. This practice is also recommended by the *Access Management Manual (1).* Almost all the states which provide any guidelines in relation to turn restrictions recommend proper channelization to restrict undesirable movements into or out of the driveways, and adequate median crossover design to accommodate left turns if required. Summary of turn restriction policies by state including rules for restricting driveway movements, driveway width and spacing criteria, and corner clearance criteria are provided in ‘*An Evaluation of Right-Turn-In/Right-Turn-Out Restrictions in Access Management’* by Lyles et al *(3).*

2.5 Summary

The review of current research on the operational evaluation of access management applications indicates limited understanding in terms of the impacts on driveway-specific and corridor-wide performance. This lack of research is realized by the TRB Committee on Access Management *(63)* which has developed ‘research needs statements’ in the areas of ‘Operational

Impacts of Access Management' (2008) and 'Minimizing Business and Development Impacts of Safety and Operational Project Treatments along Urban Arterial Corridors' (2007). The former specifically identifies the need for research on the effects of access density and spacing, access ingress and egress volumes, through traffic volumes, type of movement restrictions from access points, driveway design, and roadway cross-section on the operation of urban streets between signalized intersections. Although studies addressing similar issues are found in the literature; most of them address local issues based on field observations rather than analytical solutions that may be applicable elsewhere. Also, these studies do not tackle the issue from a corridor perspective or combine alternatives for comparison of operational outcomes. Most importantly, access-related issues at roads with TWLTL have never been addressed in a simulation environment due to the perceived level of complexity of modeling such operations especially with high-volumes.

From a traffic operations perspective, this dissertation is an attempt to quantify the impact of several combinations of access management on urban five-lane roads with TWLTL, both at individual driveways as well as at corridor levels. The variables that make-up the 142 combinations modeled in this research using VISSIM include: driveway location (corner or midblock), access control (full access or right in/out), access density, driveway volume, and through volume. The specific objectives and scope of the research, access management combinations studied, and the general approach taken for simulation modeling of the alternatives is presented in chapter 3.

CHAPTER 3

RESEARCH OBJECTIVES AND SCOPE

3.1 Problem Statement

Access management techniques have been successfully applied to improve traffic safety in many applications. One area where mobility concerns have not yet been quantified is the operational impact of access management treatments based on arterial characteristics such as traffic volumes, signalized intersection density, driveway density, driveway volume, median type, and combinations of these factors. For a given roadway type, the literature provides a wide range of criteria to determine minimum corner clearance and access density, however for an existing or a planned roadway, there lacks a consistent set of quantifiable traffic engineering criteria that accounts for the operational issues at individual driveways, adjacent intersections and unsignalized access points, and on the overall corridor. For existing roads with perceived safety issues due to high access density, the solution most often recommended in the research is to provide medians and restrict the access to right-turns-in/out only and allow for U-turns at median breaks. However, this solution is not practical in many cases, where changing the character of the entire arterial by providing median and median breaks is not economically feasible to mitigate problems at a handful of locations. While theoretically there is an infinite number of combinations of arterial characteristics, advances in simulation modeling allow for the study of most common access management alternatives on typical urban/suburban arterials in order to develop performance-based guidelines for transportation professionals on when and how to mitigate operational issues at or due to problematic driveways. The need for research in this area was recognized by the TRB Committee on Access Management.

3.2 Research Objectives and Scope

High access densities and low corner clearances on multi-lane arterials with two-way left-turn lanes (TWLTL) have a significant detrimental effect on traffic safety and mobility. In this research, the operational impacts of access modifications at midblock and corner driveways on 5-lane roads with TWLTL are quantified. The unique aspects of this research are that no major geometric changes in the corridor are made (other than signal optimization), and that modifications to corner and midblock driveways are modeled simultaneously to evaluate their localized as well as combined effect on corridor-wide operations. The overall purpose of the research is to develop operational thresholds and resulting guidelines that may be utilized to mitigate corner clearance and access density problems on urban/suburban arterials. The following are the key objectives of the research.

- Evaluate the operational impacts of several combinations of corner and midblock driveways with varying arterial through volume, driveway volume, driveway density, and access restrictions.
- Develop a methodology for the modeling of two-way left-turn lanes using micro-simulation, and apply this methodology to determine the impacts of access restriction on 5-lane arterials.
- Develop recommendations based on operational MOEs to mitigate access issues considering driveway-specific as well as corridor-wide impacts of access restrictions.

The scope of this research includes development of a base model using VISSIM micro-simulation software for a 5-lane urban arterial with a TWLTL. Based on field observations at a study corridor located in Lansing, Michigan, the base model was calibrated for traffic operations, especially driver behavior in the TWLTL, to develop theoretical models to study the effects of varying arterial and driveway characteristics. The access management alternatives studied include changing access density, restricting access from full-access to right in/out only, increasing driveway volume, increasing arterial through volume, and various combinations of these factors. The range of these variables resulted in a total of 142 theoretical models is shown in table 3.1.

Table 3.1 Factors for Theoretical Models

Factors	Levels
Arterial Volume	1500 vph (low), 1700 vph (medium), 1900 vph (high)
Access Density	0 to 44 driveways/mile (including corner and mid-block)
Driveway Volume	25 vph to 200 vph
Driveway Type	Full Access, Right In/Out, Mix

3.3 Overview of the Research Methodology

A brief overview of the research methodology is presented for the two main tasks of this effort: development and calibration of the base model including modeling of TWLTL, and development and evaluation of the theoretical models.

The base model was created for the 1.0-mile east-west section of West Saginaw Highway, from N. Creyts Road to Elmwood Road located in Lansing, Michigan. This roadway section has five lanes with a TWLTL, three signalized intersections, and a frontage road serving several developments for part of the distance. The purpose of the base model was to calibrate the driving behavior elements of the model using field data to incorporate the parameters into theoretical models. Special attention was given to model the TWLTL operations using gap acceptance for various ingress and egress movements. These were modeled in VISSIM using ‘priority rules’ for right-of-way assignments for all traffic using the TWLTL. The results of the base model were then validated with additional field data (travel times), and the TWLTL behavior was also validated separately with gap acceptance data from non-study sites with similar overall arterial characteristics. Details on the base model development and the modeling of the TWLTL are presented in chapter 4.

Theoretical models were developed that are fundamentally similar to the base model, that is, 5-lane sections with TWLTL and 1/4-mile signal spacing. For each level of arterial through volume (low, medium and high), driveway density, driveway volume, and access type were varied to create more than 150 combinations of these factors. The total combinations were ultimately reduced to 142 primarily due to upper limits on the driveway volume and corresponding TWLTL operations resulting in system-wide breakdowns. For each VISSIM model, traffic operations data were collected at more than 300 points to isolate the impacts at driveways, TWLTL, intersections, and overall corridor. The real challenge was to define the data collection points and corresponding MOEs to be used to compare the models (or treatments). It was found that arterial through volume is the most important factor that impacts the operation of corner and mid-block driveways and TWLTL operations even at low driveway volumes. The development of theoretical models and results are detailed in chapters 5 and 6.

CHAPTER 4

DEVELOPMENT AND EVALUATION OF THE BASE MODEL

4.1 Introduction

To develop theoretical models for the study of various access management alternatives, a simulation model for an existing principal arterial was created using the micro-simulation package ‘Verkehr in Städten Simulation’ (Traffic in Cities-Simulation) commonly known as VISSIM. The purpose of the ‘base model’ of an existing highway was to calibrate the driving behavior especially in the TWLTL for use in the theoretical models. VISSIM is a microscopic, time-step, behavior-based traffic simulation software that allows for the modeling of unconventional geometric and operational features such as transit signal priority, roadway construction sites, roundabouts, diverging diamond interchanges, and continuous-flow intersection among others. While an urban 5-lane undivided corridor with a TWLTL and a series of closely-spaced full-access driveways is not an uncommon corridor type, it is quite challenging to develop a simulation model for such a roadway configuration due to numerous conflict points and overlapping right-of-ways in the TWLTL. Compared to other popular simulation software such as Paramics, Sidra, and CORSIM, VISSIM’s ability to model complex features lies in the way network geometry is created using ‘links’ and ‘connectors.’ It requires that the smallest possible homogenous roadway unit for every movement in the entire network be created individually, and traffic control and driver behavior be input for each movement, and then all individual ‘links’ be joined using ‘connectors’ that provide transitional elements in the network. This practice, while making even a single intersection creation an extremely laborious exercise, allows for developing several driveway movements sharing common space in a TWLTL. The limited availability of traffic software that have a built-in TWLTL feature, and the labor-intensive modeling procedure in VISSIM (which is a relatively new software) is perhaps one of the key reasons of the limited understanding of operational effects of access management treatments on undivided corridors.

This research addresses the operational effects of access management alternatives on 5-lane undivided urban/suburban corridors with TWLTL for a range of corner and midblock driveway densities. In order to develop theoretical models based on actual driver behavior, a candidate study site was sought that provided a good mix of roadside development, through and turning volume, driveway density, driveway access type, and driveway volume. The description of the arterial ultimately selected is presented below.

4.2 Description of the Study Corridor

The study corridor is a 1-mile east-west segment of West Saginaw Highway (M-43) between Creyts Road and Elmwood Road located in Lansing, Michigan. This highway is a principal arterial that connects major freeways in the greater Lansing area and also has major traffic generators in the selected segment including a mall, strip malls, free standing superstores, office buildings, fast-food and sit down restaurants, gas stations, access roads to residential areas, and several smaller developments. General site characteristics are summarized in table 4.1, and an aerial image of the study corridor is shown in figure 4.1. These data were obtained during preliminary site visits, from web-based aerial images, and from the Michigan Department of Transportation (MDOT) website *(64)*.

Table 4.1 General Corridor Characteristics

Functional Category	Principal Arterial
Corridor Length	1 mile
Signalized Intersections	3
Intersection Spacing	1/2 mile
Intersection Cycle Length	120 sec
Posted Speed Limit	45 mph
Average Daily Traffic	31100
Commercial Traffic	2%
Pedestrian Activity	< 10/hour/intersection
Number of Driveways	33
Minimum Corner Clearance	25-ft
Maximum Corner Clearance	400-ft
Minimum Driveway Spacing	35-ft
Maximum Driveway Spacing	400-ft
Minimum Driveway Turning Volume	4 vph
Maximum Driveway Turning Volume	150 vph

Figure 4.1 West Saginaw Highway Study Corridor in Lansing, MI (For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation).

4.3 Field Data Collection

An extensive field data collection exercise was conducted at the site to determine microscopic parameters for input and for calibration of the simulation model. The data were collected over nine weekdays in November 2009 during morning, afternoon, and evening peak hours. These data included intersection turning volumes, signal timings and phasing, saturation flow rates, start-up loss times, queue lengths, pedestrian activity, driveway turning volumes, driveway control, turning restrictions, corridor travel times, and gap acceptance for all movements using the TWLTL. These data were collected using the methods and worksheets provided in the Highway Capacity Manual *(65)*. The evening peak hour from 5 pm to 6 pm emerged as the most critical in terms of through and turning volumes at signalized intersections, as well as highest driveway volumes during the day. The volumes were collected in 5-minute intervals, and the peak hour factor (PHF) was computed to be 0.96. The signalized intersection hourly volumes by turning movements during the PM peak hour (5 pm to 6 pm) are shown in table 4.2.

Table 4.2 Intersection Turning Volumes during PM Peak Hour

Turning Movement	**Eastbound**			**Westbound**			**Northbound**			**Southbound**		
	L	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**
Creyts Road	121	1008	167	140	1173	163	266	355	300	205	189	116
Mall Drive	178	1215	120	97	1097	40	218	115	110	49	82	161
Elmwood Road	190	1042	169	169	1019	239	139	285	227	263	221	104

The saturation flow rates were computed for each movement at the signalized intersections, and the overall average saturation flow rate for the corridor was computed to be 1897 vehicles per hour per lane (vphpl) which is very close to the ideal saturation flow rate of 1900 vphpl. The average startup loss time came out to be 1.89 seconds. Very little pedestrian crossing activity was observed in the corridor during the evening peak hours.

Turning volumes at access points for adjacent developments were also collected and ranged from 4 vehicles per hour (vph) at the only single-family home located in the corridor to 150 vehicles per hour at the Meijer free-standing superstore. Driveway turning restrictions ranged from full-access to right-in/out only movements, and several other combinations including right-in and left-out, right-in/out and left-out, right-in/out and left-in, and right-out and left-in only movements. A significant number of violations of access restrictions were observed despite restrictive geometry and signage.

Travel time data were collected using the floating car method for calibration purposes. Seven runs in each direction in the corridor were made, and the average east-bound travel time was found to be 195.66 seconds (including the stop delay time at signalized intersections or when vehicle speed dropped below 5 mph). The average west-bound travel time was computed as 218.39 seconds including stop delay.

In order to model driveway ingress and egress movements that utilize the TWLTL, gap acceptance (in seconds) was measured for each movement. VISSIM defines a minimum gap time that a vehicle waiting to turn will accept in order to complete the turn before an approaching vehicle enters the conflict area (defined under ‘priority rules’). This is described in detail in section 4.4.1. The minimum gap time was observed for vehicles turning right-out, left-in from the TWLTL, or left-out (either in TWLTL or directly onto the through-lane) from the driveways.

These observations were made at the study site, as well as several other driveways located on similar arterials in the area for validation purposes (sample size > 100 for each driveway movement observed). Table 4.3 shows gap acceptance data that were used in the simulation. Note that extreme values such as very short gap times displaying aggressive behavior (less than three seconds) and very long gaps which were not affected by potentially conflicting traffic (greater than six seconds) were excluded from the observations.

Table 4.3 Driveway Gap Acceptance Data

Driveway Movement	Minimum Gap Time (sec)	Maximum Gap Time (sec)	Average (sec)
Left-Out	3.1	5.9	4.8
Left-In from TWLTL	3.6	5.6	4.6
Right-Out	3.0	5.7	4.7

The field data along with the geometric data obtained mostly from aerial images were used to create the base simulation model as described in the next section.

4.4 Development of the Base Simulation Model

The geometric and traffic data were used to first create a model for the PM peak hour using the ‘Synchro’ software package which is used as a preprocessor for VISSIM. The Synchro model was primarily utilized to test the signal timings and to reconcile volume differences between driveways. VISSIM does not have the capability of optimizing the signal timings; therefore Synchro models were created first for the base conditions as well as for all theoretical models for the purpose of optimizing the signal timings and offsets with the given volumes. Note that optimization was not done for the existing conditions and signal timings observed in the field were utilized to generate results.

While VISSIM is capable of accurately translating Synchro networks with simple geometry and thus reducing the modeling effort; this was not possible in this case due to Synchro's limited capability to model complex geometry such as a TWLTL. Therefore the VISSIM model was created by manually drawing individual links and connectors based on a background site image. In order to draw the TWLTL, overlapping links were drawn and movements were controlled using 'priority rules' as described in the next section.

Vehicle composition was defined in VISSIM that included two vehicle types: cars and 'heavy goods vehicle' (HGV) with relative flows of 98% and 2% respectively. The stochastic desired speed distribution for each vehicle type was defined as default with an initial minimum value of 35.8 mph and a maximum value of 43.7 mph.

Intersection and driveway control elements such as signals with National Electrical Manufacturers Association (NEMA) phasing and stop signs were coded at specific locations. Vehicle input volumes were added at entry points and static routes were defined for all allowable movements in the network. The driveway traffic was distributed based on observed volumes, and was split at intersections based on intersection turning volume ratios.

Data collection points, travel time sections, and intersection nodes were defined to generate outputs. The simulation was set to run for 70 minutes with the first 10 minutes for warm-up time to fill the network. The data collection period was set to start after the initial warm-up time. The simulation speed was set to maximum at 10 simulated seconds for every real time second. The simulation resolution which defines the number of times a vehicle's position is computed in each simulated second was set at 5 per simulation second. A maximum value of 10 was not used due to its adverse effect on the actual simulation running time, which increased from 45 minutes per run to about 120 minutes per run due to the size of the network and the number of data collection points. A total of three runs for all models (base and theoretical) were simulated, with each run starting with a new random seed. A schematic of the base model showing various elements is shown in figure 4.2.

4.4.1 Simulation Modeling of the Two-Way Left-Turn Lane (TWLTL)

The complexity of modeling a TWLTL stems from the need of opposing vehicles to occupy common space, especially under high driveway volume conditions. In VISSIM, the TWLTL can be modeled indirectly using 'priority rules' which assign right-of-way to potentially conflicting vehicular movements on different links and connectors. A 'priority rule' is defined by two components: a stop line where vehicles wait before completing the turning movement, and 'conflict marker(s)' which checks current conditions (at every simulation time-step) to allow the waiting vehicle to initiate the turn based on the availability of space ('minimum headway') or time ('minimum gap') *(21)*.

'Minimum headway' in VISSIM is defined as the length of the conflict area, typically set equal to the space occupied by one vehicle *(21)*. The availability of minimum headway is checked by the conflict marker under congested or queuing conditions in the model.

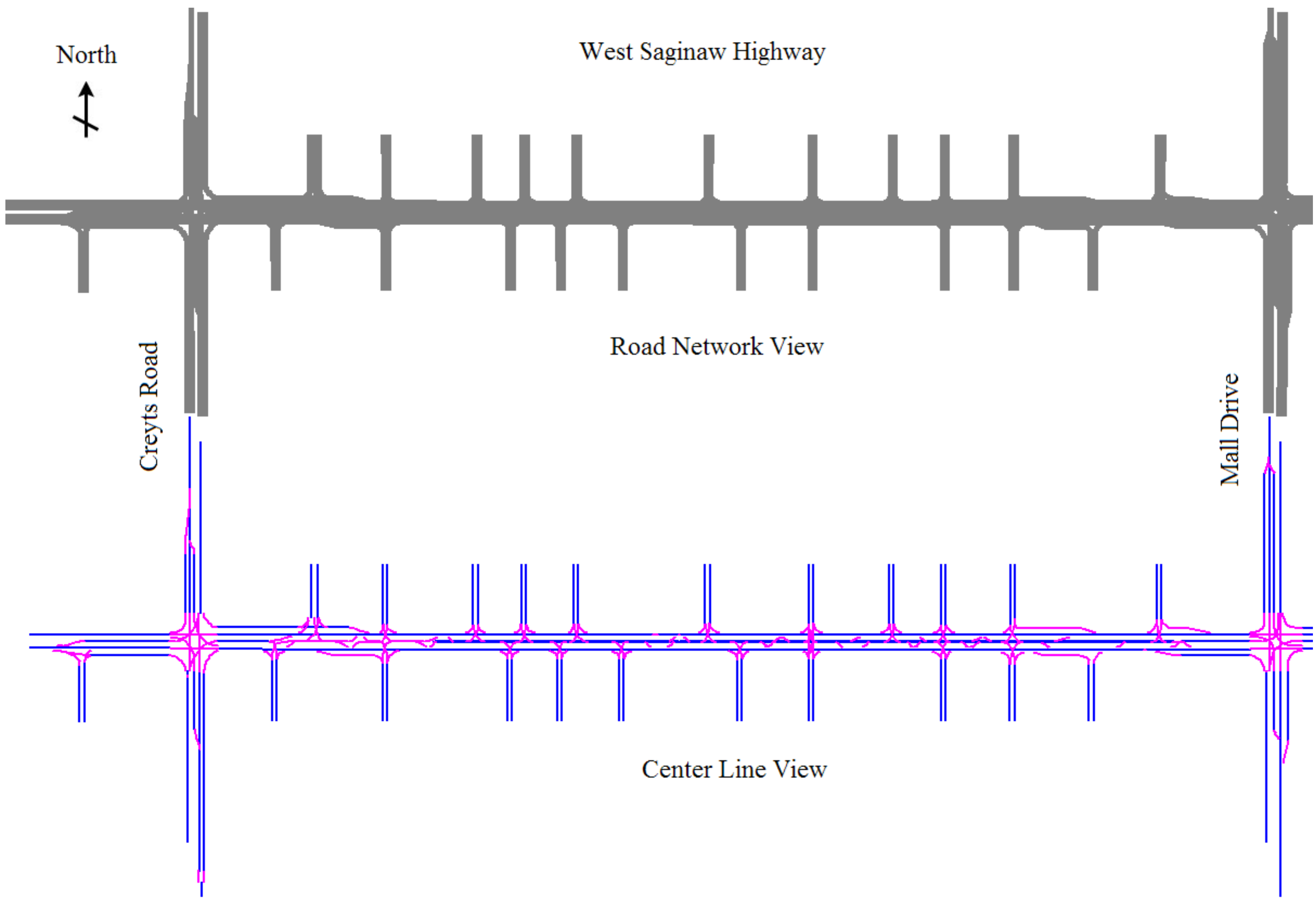

Figure 4.2 Base Model in VISSIM

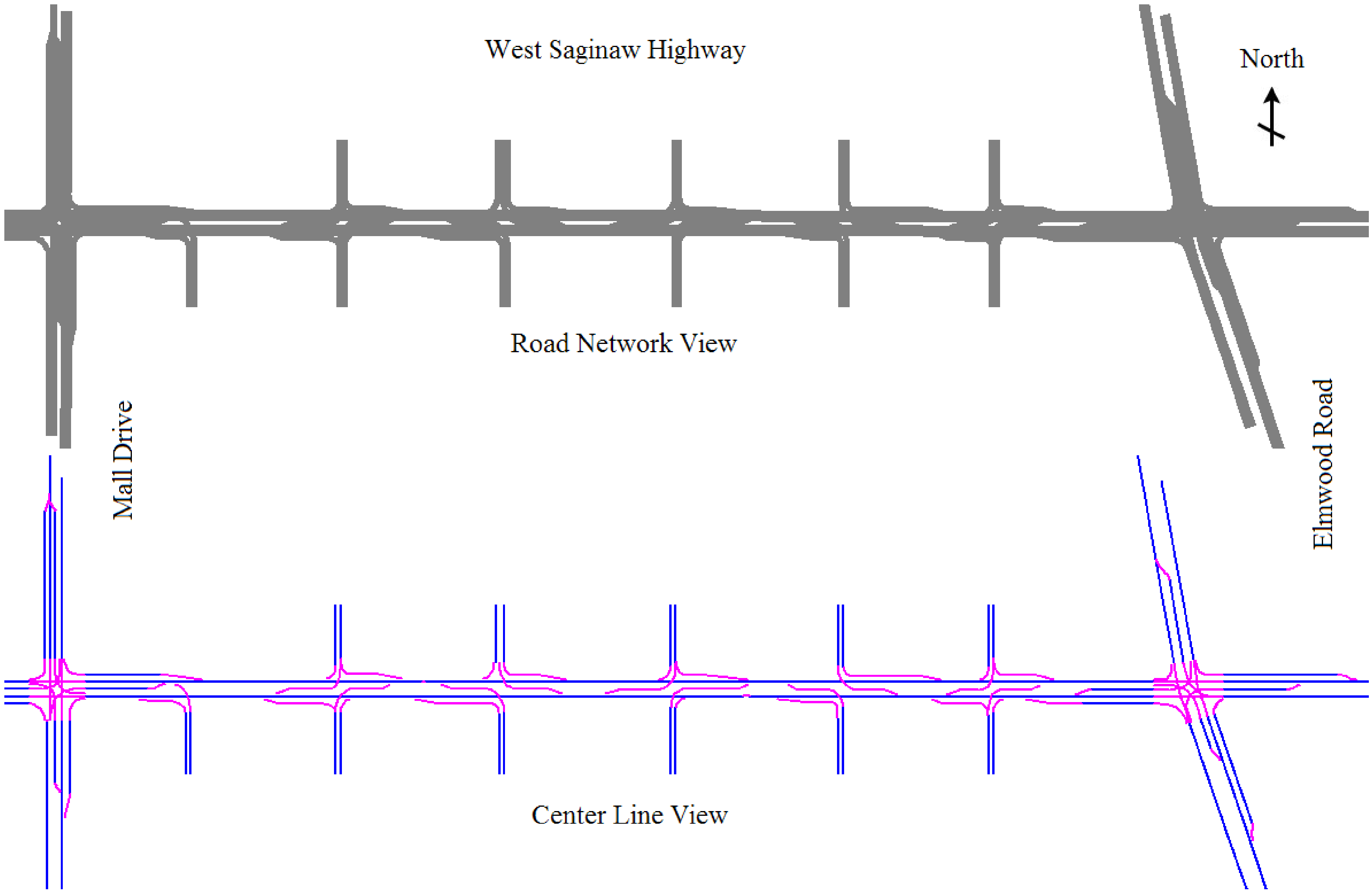

Figure 4.2 (cont'd)

‘Minimum gap’ is defined as the time (in seconds) an approaching vehicle will take to reach the conflict marker at its current speed. The minimum gap condition is checked by the conflict marker under free-flow conditions on the corridor. The values used for ‘minimum gap’ for various movements based on field observations and as recommended by Eisele et. al. *(30)*, are shown in table 4.3. Note that VISSIM does not allow for inputting a range or distribution of the gap times and only minimum values are accepted. However, this may be mitigated by strategically locating the conflict markers in relation to the path of the turning vehicle.

Modeling of a TWLTL using priority rules was qualitatively evaluated by Dale and Woody *(20)* in which a pair of midblock opposing driveways with a spacing of 75-ft were modeled in VISSIM using connectors only instead of a continuous left-turn lane. In their modeling approach, the researchers used left-in and left-out volumes of approximately 100 vph per driveway, with left-in traffic modeled on transit routes for illustrative purposes. While the objective of their research was to assess the utility of simulating various access management techniques primarily for presentation purposes, the example provided in the paper demonstrated the use of priority rules for the control of TWLTL traffic and was used as the starting point in this research.

Before simulating TWLTL operations for the entire study corridor, extensive testing was done for a number of scenarios in terms of orientation of opposing driveways. Modeling of typical corner and midblock full access driveway movements is illustrated below.

Figure 4.3 shows an example with a set of corner driveways, one on each approach and departure side of a signalized intersection with two through lanes in each direction. The driveways are located at 150-ft (edge to edge) from the intersection and the right- and left- turn bays at the intersection extend 250-ft. In the ‘center line’ view of the driveways showing links (blue) and connectors (pink) for individual movements, components of the priority rules are shown with stop lines (red) and conflict markers (green). No priority rules are needed for right-in movements for any driveway. The meanings of different notations in described next.

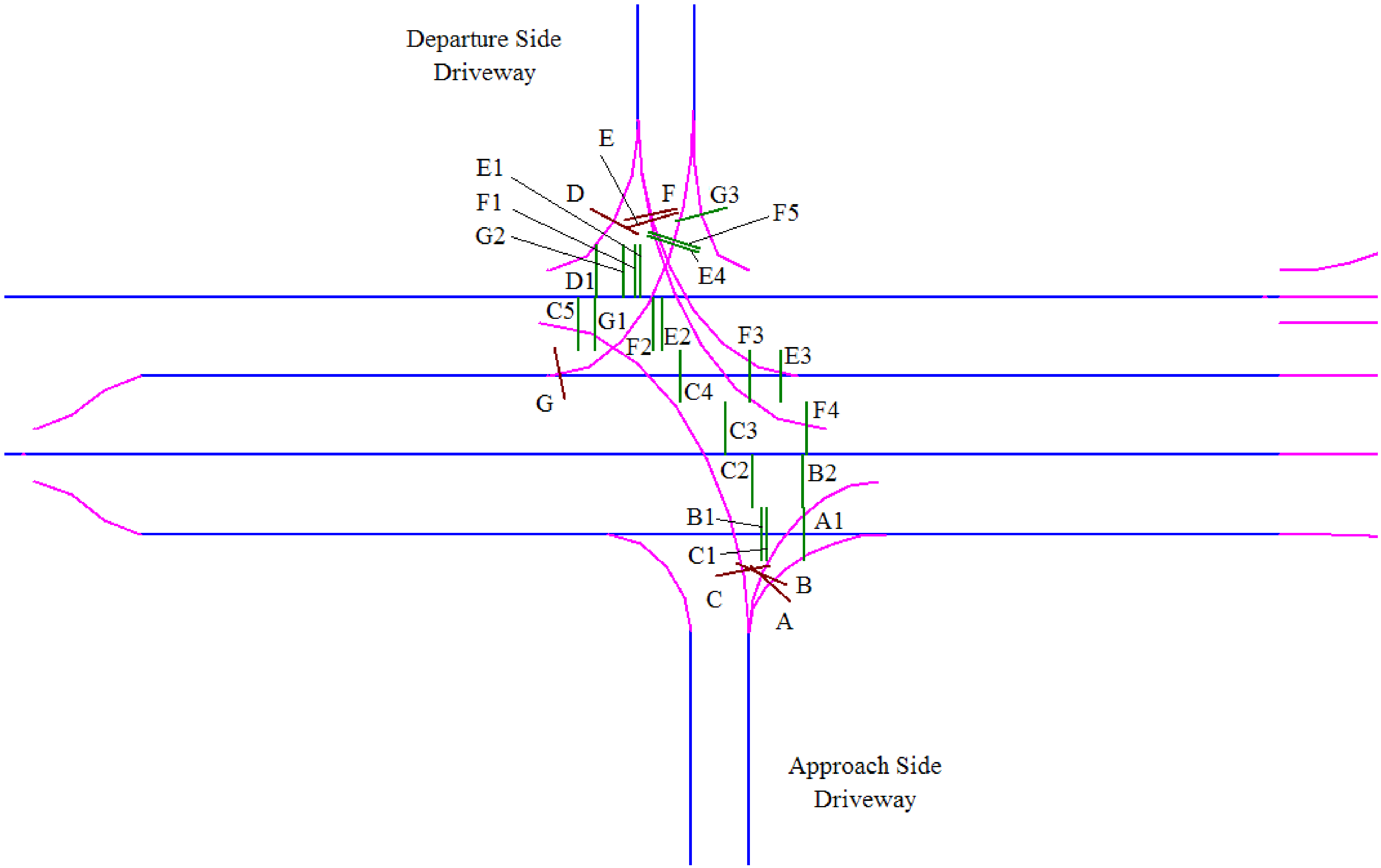

Figure 4.3 Priority Rules for Corner Driveways

For a driveway on the approach side, all movements are permitted except the left-in movement because of its direct conflict with the traffic turning left at the intersection. For right-out traffic from the driveway, vehicle routes are coded to allow for right turn at the intersection using the right-turn bay and also straight through the intersection. For vehicles routed to turn right at the intersection, a stop line is introduced on the connector at location ‘A’ as shown in figure 4.3, and a conflict marker is placed in the right-turn bay link at location ‘A1’ in the projected path of the turning as well as approaching vehicle. This conflict marker is to assure the availability of minimum headway and/or minimum gap time for the turning vehicle to safely complete the maneuver without colliding with approaching traffic in the right-turn bay.

For vehicles routed to go straight through the intersection, a stop line is introduced on the connector at location ‘B’, and two conflict markers are placed. Conflict marker ‘B1’ is placed in the right-turn bay link at a location in the projected path of the approaching vehicle, and conflict marker ‘B2’ is placed in the through-lane in the projected path of the turning as well as approaching vehicle. Again, these conflict markers check for minimum distance or time before allowing the vehicle at the stop line to move.

Vehicles turning left from the approach-side driveway must clear 4 lanes of traffic (two through and two turning lanes) before completing their turn in the inside lane. To establish priority rules for this movement, a stop line is introduced on the connector at location ‘C’, and five conflict markers are placed. Conflict markers ‘C1’ through ‘C4’ are placed to ensure safe passage from traffic approaching the intersection in various lanes, and conflict marker ‘C5’ is placed for clearance from the traffic leaving the intersection in the inside lane. All conflict markers are placed along the projected path of the turning vehicle in such a way that more gap time is available from the vehicles in far lanes as the turning vehicle moves away from the stop line to complete the turn.

For the driveway on the departure side, priority rules for right-out movement are coded as described before for the approach side. The stop line is labeled as ‘D’ and the conflict maker as ‘D1’ in figure 4.3. The left-turning traffic is routed to either turn left at the intersection or go straight through. Separate sets of priority rules are specified in each case.

For left-turning traffic from the driveway turning left at the intersection, a stop line is introduced on the connector at location ‘E’, and conflict markers are placed at ‘E1’ and ‘E2’ in the through lanes. Conflict marker ‘E3’ is placed in the left-turn bay to avoid conflict with the traffic turning left at the intersection. Conflict marker ‘E4’ is placed in the projected path of the traffic turning left into the driveway such that a vehicle at the stop line ‘E’ will yield right-of-way to the vehicle already waiting to turn into the driveway (at ‘G’).

For left-turning traffic from the driveway going straight through the intersection, a stop line is introduced on a separate connector at location ‘F’, and conflict markers are placed at ‘F1’ and ‘F2’ in the through lanes. Conflict marker ‘F3’ is placed in the left-turn bay to avoid conflict with the traffic turning left at the intersection. Conflict marker ‘F4’ is placed for clearance from the traffic approaching the intersection in the inside lane. Conflict marker ‘F5’ is placed to yield right-of-way to the vehicle already waiting to turn into the driveway (at ‘G’) as described for ‘E4’.

For vehicles routed to turn left-in from the mainline into the departure-side driveway, priority rule with a stop line at ‘G’ is introduced in the left-turn bay. Conflict markers ‘G1’ and ‘G2’ are placed on the opposing through lanes in the projected path of the turning vehicle, and conflict marker ‘G3’ is placed to yield right-of-way to the traffic turning right into the same driveway.

Figure 4.4 shows an example with three midblock full-access driveways with a spacing of 150-ft (edge to edge). In the ‘center line’ view of the driveways showing links (blue) and connectors (pink) for individual movements, components of the priority rules are shown with stop lines (red) and conflict markers (green). A series of links and connectors are added in the middle of the through lanes to simulate TWLTL operations.

Movement-specific priority rules were added for all driveways using the same logic defined previously for the corner driveways. Some additional considerations regarding TWLTL modeling are described here. Note that the priority rules for similar driveways are not located at identical locations due to minor differences in geometry such as curvature of the connector. No priority rules are added for right-in movements for any driveway.

In each driveway, for vehicles turning right from the driveway, a stop line is introduced on the connectors at locations ‘A’, ‘B’, and ‘C’ as shown in figure 4.4. Conflict markers are placed for respective stop lines in the outer through lanes in the projected path of the turning as well as approaching vehicles at ‘A1’, ‘B1’, and ‘C1’.

A vehicle turning left into ‘Driveway X’ is routed to first enter the TWLTL link at ‘Connector M‘. In the example illustrated in figure 4.4, the driveway left-in traffic has approximately 80-ft of space available (length of ‘link’ in VISSIM) for queuing inside the TWLTL. A stop line is placed at location ‘D’ and corresponding conflict markers are placed at ‘D1’ and ‘D2’ for the opposing through traffic and at ‘D3’ for traffic turning right into the driveway. A similar scheme is repeated for each driveway’s left-in movement.

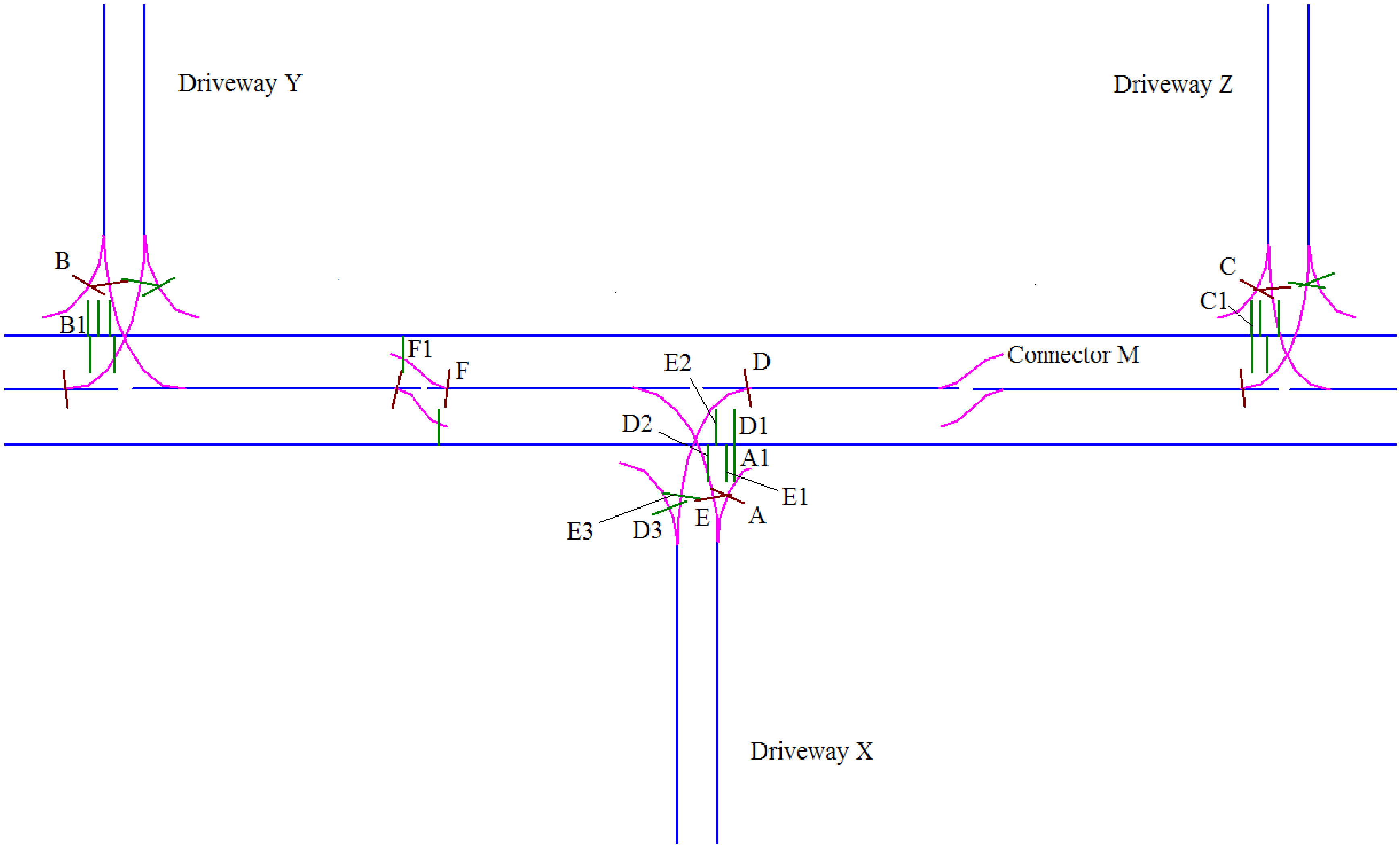

Figure 4.4 Priority Rules for Midblock Driveways

For the left-out movement for ‘Driveway X’, priority rules are added by placing a stop line at ‘E’ with conflict markers placed at ‘E1’ and ‘E2’ for through lanes, and at ‘E3’ for the vehicle turning left into the driveway from the TWLTL. The left-out vehicle must additionally stop in the TWLTL link at location ‘F’ before merging with the traffic in the inside through lane using ‘Connector N’. This part of the TWLTL is also approximately 80-ft long in this example. A conflict marker ‘F1’ corresponding to stop line ‘F’ is placed on the through lane to eliminate potential conflicts between the merging and the through traffic. Left-in and -out movements from driveways ‘Y’ and ‘Z’ are modeled in the same fashion. Note that the driveway entry and exit connectors are placed approximately mid-way between successive driveways in a way that essentially eliminates the problem of conflicting traffic using the same space within the TWLTL.

As shown in figure 4.2, corner and midblock driveways from Creyts Road to Mall Drive were modeled (for the most part) using a continuous set of overlapping links with connectors to and from the mainline and the TWLTL with movement-specific priority rules as defined above. On the other half of the study corridor between Mall Drive and Elmwood Road, individual driveway movements are modeled using connectors only. In the former case, overlapping links were necessary due to closely-spaced driveways, whereas in the latter case where driveway spacing is far enough as not to be impacted (or conflicted) by the traffic in or out of the adjacent driveway, modeling using connectors only was found to be functionally adequate based on visual observations. In theoretical models however, all TWLTL operations were modeled using overlapping links even under low driveway density conditions for ease of data collection and comparison.

Figures 4.5 and 4.6 illustrate priority rules as implemented at various locations in the study corridor. Figure 4.5 shows a set of driveways located just east of Creyts Road where driveway movements were modeled using connectors only. This figure also shows an example of priority rules when opposing driveways are located directly across from each other. Figure 4.6 shows a set of closely-spaced midblock driveways between Creyts Road and Mall Road, where the TWLTL was modeled with overlapping links. This particular segment of the study site illustrated the limitation of the VISSIM model where entry and exit points for closely-spaced driveways cannot be overlapped due to lack of space, instead a single entry and a single exit point must be defined for more than one driveway with additional priority rules which may not be representative of the actual driving behavior. For the study site, however, this was not a significant problem operationally due to extremely low volumes at these driveways. This limitation was considered in the development of theoretical models to determine the minimum allowable driveway spacing that can be modeled with separate entry and exit locations per driveway on the TWLTL as shown previously (figure 4.4).

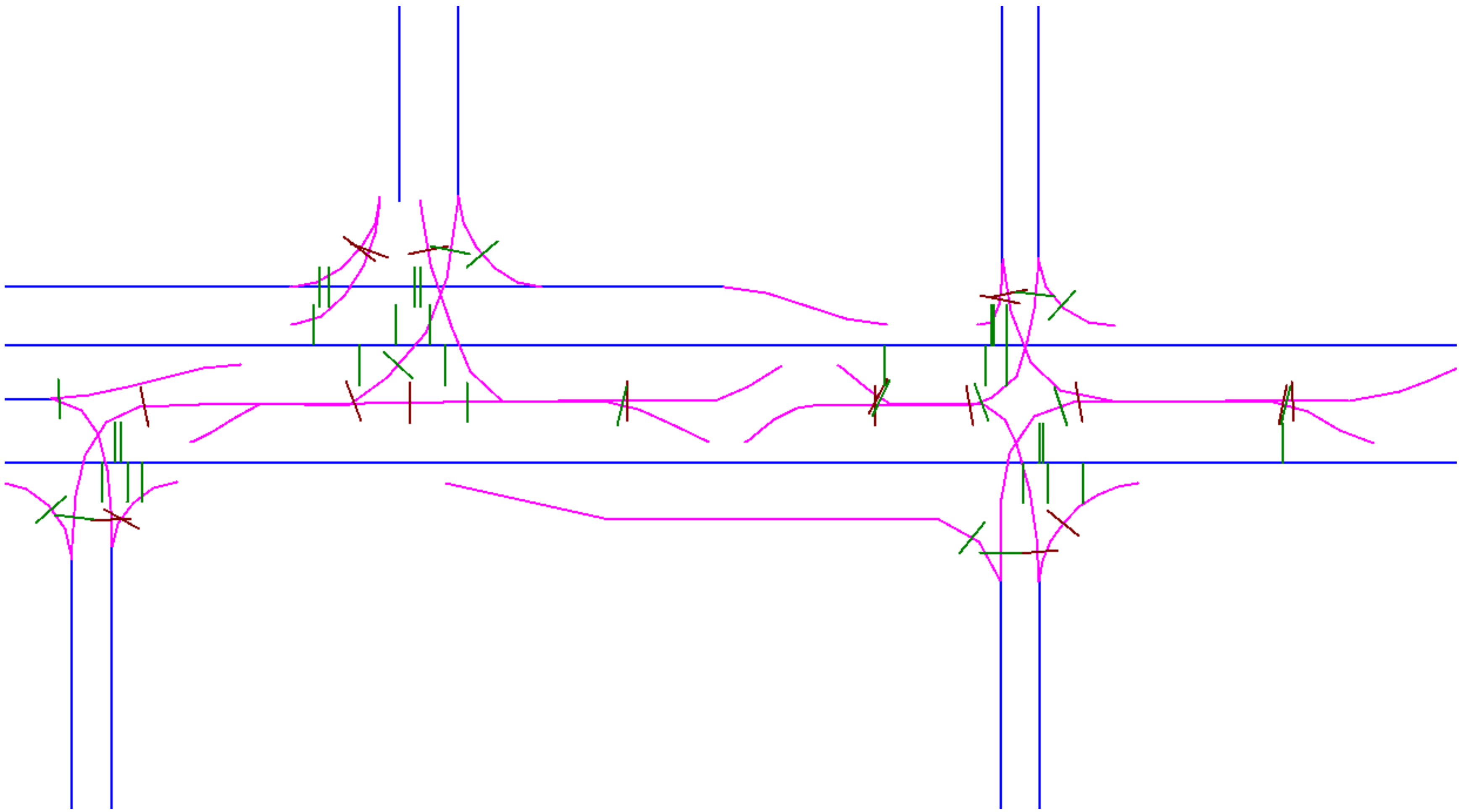

Figure 4.5 Priority Rules using Connectors only

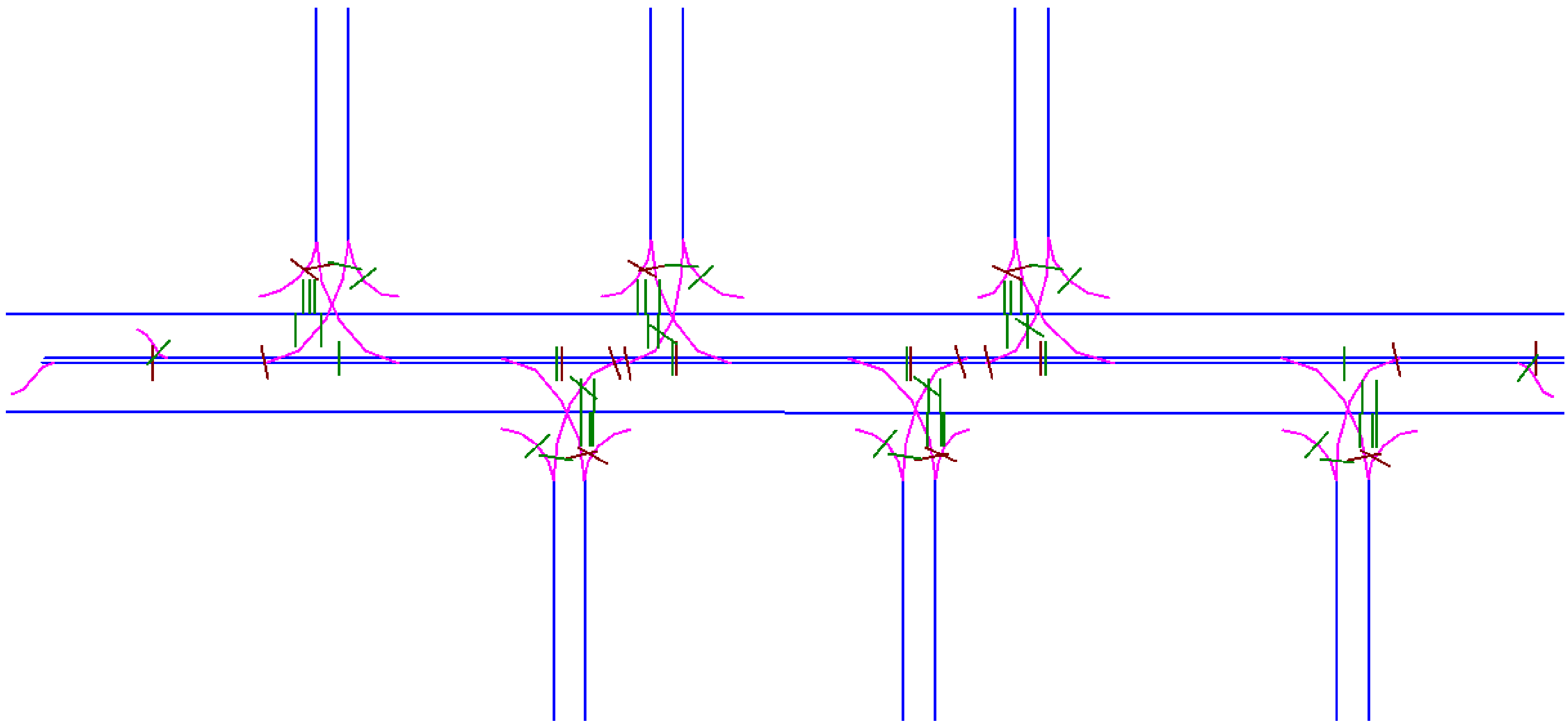

Figure 4.6 Priority Rules using Overlapping Links

4.5 Model Calibration

To ensure that the base model accurately represented the existing conditions, it was tested and calibrated using the travel time data. First a visual inspection was done for the entire network and for each run, especially examining the operations at TWLTL to detect conflicts. The location of 'conflict markers' were adjusted at some connectors where they appeared to yield to the vehicle waiting to turn (i.e., yielding to self), especially at transitional locations between TWLTL and left-turn lanes at signalized intersections. No other significant adverse behavior was observed in the network, and the operations at the driveway with the highest volume (150 vph) also seem to be appropriate with no significant conflicts or stacking of vehicles in the TWLTL.

The field travel time data was compared to the simulation output and it was found that the VISSIM output resulted in slightly higher travel times in the corridor. The eastbound travel time (including stop delay) observed in the field was 195.66 seconds and the average value from three simulation runs was found to be 204.37 seconds. The westbound field travel time was 218.39 seconds whereas the simulation results indicated 224.58 seconds.

The signal timings and coordination offsets were rechecked to ensure comparable delays between Synchro and VISSIM intersection-related results. It was found that the average delay from the two software estimates for the intersections were within three seconds with Synchro delays slightly higher overall. This indicated a need to adjust the desired speed distribution, which was varied iteratively until the VISSIM travel times were within 2% of the field values for both directions. The desired speed distribution range for cars initially set from 35.8 mph to 43.7 mph was increased to a range between 40.3 mph and 49.2 mph. The speed adjustment reduced the model travel time for eastbound to 195.75 seconds and westbound to 213.30 seconds.

4.6 Results

The results were obtained from data collection points, travel time sections, and intersection nodes defined in the VISSIM network. The outputs were generated in each simulation time-step, aggregated for the analysis hour, and averaged for all three runs. Key corridor-wide results are summarized in table 4.4, and intersection delays (seconds/vehicle) and corresponding levels of service (LOS) are summarized in table 4.5.

Table 4.4 Corridor-wide Results

Corridor Volume Simulated (vph)	7085
Total Driveway Volume (vph)	1335
Total Travel Time (h)	252.00
Total Delay (h)	144.24
Total Stop Delay (h)	95.17
Average Speed (mph)	18.05
Average Delay (s/veh)	73.28
Average Stop Delay (s/veh)	48.35
Average Number of Stops per Vehicle	1.66
Average Driveway Delay (s/veh, All Movements)	77.79

Table 4.5 Base Model Intersection Level of Service

	Eastbound		**Westbound**		**Northbound**		**Southbound**		**Overall**	
	Delay	**LOS**	**Delay**	**LOS**	**Delay**	**LOS**	**Delay**	**LOS**	**Delay**	**LOS**
Creyts Road	31.0	C	35.4	D	40.9	D	38.6	D	35.6	D
Mall Drive	31.1	C	35.9	D	28.5	C	23.9	C	31.9	C
Elmwood Road	31.7	C	29.8	C	37.3	D	48.3	D	34.3	C

4.7 Utility for Theoretical Models

The development and calibration of the base model in VISSIM provided important input parameters for the theoretical models including vehicle composition and relative speed distributions, and use of priority rules including gap acceptance times and minimum headways. In addition, this exercise provided valuable lessons in the modeling of a TWLTL in terms of using links vs. connectors, location and setup of static routing decisions, access restrictions at corner driveways, maximum driveway spacing that can be modeled in VISSIM, differences in modeling approach based on driveway placement in relation to the driveway on the opposite side of the road, and systematic location of data collection points in the network for comparison between various theoretical models.

It was found that using either links or connectors to model TWLTL operation did not matter - the choice did not have any effect on the movement of driveway vehicles, especially if the driveway spacing is more than 200-ft. However, use of overlapping links is more realistic and recommended for shorter driveway spacing. Even though connectors alone are relatively simpler to model for various driveway movements, links allow for better control on the location of priority rules and are easier to modify. For cases where a development may be served by multiple driveways or when frontage roads are present, using links instead of connectors will also allow for using ‘dynamic’ routes, where a vehicle may use the next available driveway entrance if the first route is already congested.

Traffic volumes in VISSIM are input for each link and for each time interval. In all the models for this research, the time interval was defined as 1-hour in which the vehicles enter based on a Poisson distribution. Since the volumes are not defined at nodes (intersections or driveways), additional information on routing decisions was input for all movements in the network using fixed percentages for each origin-destination ('static' routes). Given high access density, several schemes were tested to provide static routes in a manner that eliminated or minimized the number of vehicles unable to complete the assigned route due to a route origin placed too close to the next connector.

A number of access restriction alternatives were tested for the corner driveways in order to determine the type of movements that the software can model without any conflicts with the through or turning vehicles at the signalized intersections. This testing was done separately for corner driveways at approach and departure sides of the intersection. At corner driveways on the approach side, it was determined that left-in movement for the driveway was not possible to model where the turning vehicle had to occupy the intersection left-turn pocket and hence be in direct conflict with the approaching traffic. While this type of movement on actual arterials is generally prohibited; it was observed at the study site that some motorists made such turns despite physically prohibitive driveway entrances and/or signage.

At corner driveways on the departure side, a full-access driveway was successfully modeled even if the corner clearance was significantly shorter than the length of turning bays (right or left). However, in such cases separate connectors are needed for left-out traffic depending on its ultimate destination. At departure side corner driveways located at distances approximately equal to the length of turning bays, the modeling of left-in and -out movements proved to be more complex due to the confluence of several intersection and driveway connectors.

As shown in table 4.1, midblock driveway spacing in the study corridor ranged from 35-ft to 400-ft. The base model allowed for the modeling of TWTLT serving driveways spaced very closely, and the range of driveway volumes under which this arrangement of driveways was adequate from a theoretical modeling perspective. Closely-spaced driveways in the base model had volumes utilizing the TWLTL up to 24 vph which were successfully modeled without apparent conflicts. A sensitivity analysis was conducted to determine the maximum driveway volume and corresponding minimum midblock driveway spacing that may be modeled without creating congested conditions in the TWLTL. This distance was determined to be 110-ft for driveway volumes of up to 200 vph (all movements combined). These upper limits on spacing and volumes helped in the development of the various theoretical scenarios tested in this research.

For data collection within the simulation model, VISSIM provides a number of options including separate output for each link, data collection by defining nodes and travel time sections in the network, data collection at specific points, and by defining queue counters. Simulation outputs were generated using these and other available options in VISSIM to determine a uniform data collection scheme that could be utilized for all the theoretical models. As a result of this exercise, three output options were selected including node evaluation for intersections and corridor-wide data, data collection points for driveway and TWLTL evaluation, and travel time sections for route-specific data. These outputs are generated by the software in three different formats: text, Microsoft Access database files, and Microsoft Excel. A coding scheme was developed for the location of various data collection points in the model, as well as for output files for an organized evaluation of 142 different theoretical scenarios which generated more than two million pieces of data across all models.

The development and evaluation of the base model provided the foundation to test the operational impact of access management alternatives on theoretical corridors that depict realistic driving behavior under varying conditions as described in chapter 5.

CHAPTER 5

DEVELOPMENT OF THE THEORETICAL MODELS

5.1 Introduction

One of the key objectives of this research is to study the relationship between traffic operations and access management on 5-lane undivided highways. A systematic approach was taken to develop theoretical models in VISSIM that incrementally altered mainline through volume, driveway density, driveway volume, and driveway turning restrictions. The main reason access management alternatives were studied in a simulation environment is that there are a large number of combinations based on geometric and traffic characteristics that affect corridor operations. Developing simulation-based models provides better control over inputs and, subsequently, allows studying comparable outputs of various scenarios as described below.

5.2 Description of Theoretical Models

The theoretical models were based on arterial functional and design characteristics provided in the Highway Capacity Manual *(65)* for urban and suburban arterials. These include estimates on access density, signals per mile, roadside development, service volume, peak-hour factor, and percentage of left and right turns at the intersections. Similar to the base model for the study corridor, all theoretical models were created to be 1-mile long with a signal spacing of ¼-mile. The mainline input volumes at the corridor entry links were set at three levels: low (1500 vph in each direction), medium (1700 vph in each direction), and high (1900 vph in each direction). At signalized intersections, the traffic was split at 10% each for right and left turns. A peak hour factor of 0.92 was used for signal optimization (based on typical conditions from

HCM). No pedestrians were considered in the theoretical models. The side-street traffic volumes varied between 400 and 700 vph per direction, and these volumes were kept constant in all theoretical models.

To establish baseline conditions, corridors without any driveways were created with five signalized intersections for each of the three mainline volume levels. Then, several combinations were produced for driveway locations including corner driveways and/or midblock driveways in the theoretical corridors. All corner driveways were located 150 feet from the signalized intersections and were located only on the mainline. No driveways were modeled on the side-streets. The midblock driveway density varied between 8 driveways/mile and 24 driveways/mile.

The driveway access control was modeled as full-access, right-in/out only, or a combination of the two. The driveway volumes ranged from 25 vph to 200 vph for all permissible movements. These ranges were defined after initial testing in various scenarios to determine the upper limits on the driveway volume based on congested conditions with a TWLTL for a given mainline volume. The driveway volume was kept uniform for each driveway type in a given model in order to control the distribution of traffic within the corridor.

Table 5.1 shows all 142 theoretical models developed for this research. In order to distinguish between various models, a nomenclature is developed as shown under 'Label' in table 5.1. For example, in case 'C20/RR-M8/FA,' 'C' stands for corner driveways and 'M' for midblock driveways. The number following each C or M designation is the number of respective driveways in the corridor. 'FA' and 'RR' represent the type of driveways as either 'full access' or 'right-in/out'.

Table 5.1 Combinations of Theoretical Models

Driveway Characteristics			Mainline Volume (vph)			Label
Location	**Access Control**	**Density**	Low (1500)	Medium (1700)	High (1900)	**Label**
			Driveway Volume (vph)			
No driveways, only intersections with varying mainline volumes						Baseline
Corner	Full Access	20	50	25	25	C20-FA
			100	50	50	
			150	100	100	
	Right In/Out	20	50	50	50	C20-RR
			100	100	100	
			150	150	150	
Midblock	Full Access	8	100	100	50	M8-FA[1]
			200	200	100	
			n/a		200	
		16	100	100	100	M16-FA
			200	200	200	
		24	100	100	50	M24-FA
			150	150	100	
			200	200	200	
	Right In/Out	8	100	100	100	M8-RR
			200	200	200	
		16	100	100	100	M16-RR
			200	200	200	
		24	100	100	100	M24-RR
			200	200	200	

Table 5.1 (Cont'd)

Driveway Characteristics			Mainline Volume (vph)			Label
Location	Access Control	Density	Low (1500)	Medium (1700)	High (1900)	
			Driveway Volume (vph)			
Corner and Midblock (20 corner driveways, remaining midblock driveways)	Full Access	28	50	50	50	C20-M8-FA
			100	100	100	
			150	25 (corner) 150 (midblock)	25 (corner) 150 (midblock)	
		36	50	50	50	C20-M16-FA
			100	100	100	
			150	25 (corner) 150 (midblock)	25 (corner) 150 (midblock)	
		44	50	50	50	C20-M24-FA
			100	100	100	
			150	25 (corner) 150 (midblock)	25 (corner) 150 (midblock)	
	Right In/Out	28	50	50	50	C20-M8-RR
			100	100	100	
			150	150	150	
		36	50	50	50	C20-M16-RR
			100	100	100	
			150	150	150	
		44	50	50	50	C20-M24-RR
			100	100	100	
			150	150	150	

Table 5.1 (Cont'd)

Driveway Characteristics			Mainline Volume (vph)			Label
Location	Access Control	Density	Low (1500)	Medium (1700)	High (1900)	
			Driveway Volume (vph)			
Corner and Midblock (20 corner driveways, remaining midblock driveways)	Full Access + Right In/Out	28 (midblock full access, corner right in/out)	50	50	50	C20/RR-M8/FA[2]
			100	100	100	
			150	150	150	
		36 (midblock full access, corner right in/out)	50	50	50	C20/RR-M16/FA
			100	100	100	
			150	150	150	
		44 (midblock full access, corner right in/out)	50	50	50	C20/RR-M24/FA
			100	100	100	
			150	150	150	

[1]The number of driveway volume levels depends on the observed delay and the corresponding LOS for the extreme case modeled. For example, for the case with eight midblock full-access driveways (M8-FA), the average delay per driveway at 200 vph for both 1500 vph and 1700 vph mainline volume was found to be less than 10 s/veh (LOS A). For the same case, at 1900 vph mainline volume, the LOS at 200 vph was 'C,' therefore a range of driveway volumes was modeled to determine the variation in delays for the high mainline volume case.

[2]'C' stands for corner, 'RR' for right-in/out, 'M' for midblock, 'FA' for full-access, and the number following 'C' or 'M' indicated the number of driveways for the respective driveway location in the model.

5.3 Simulation Modeling in VISSIM

The theoretical models were created in VISSIM using the same methodology as described for the base model. Signal timings for different intersection volumes were separately optimized using Synchro and used as inputs to VISSIM. The signal timings were optimized to reduce delay for the mainline traffic in each model, and coordination offsets were also computed and input in the VISSIM models. In terms of corridor geometry, 18 separate models were created as shown in table 5.1. A model is defined as a combination of driveway location, access control, and density. For each of the 18 models, mainline volumes, driveway volumes, and corresponding routing decisions were added to create 142 separate scenarios. The driveway ingress and egress volumes were specified in a way to equally distribute the traffic to and from the mainline. This was primarily done for ease of computation of corridor-wide static routes, and also to minimize the variation in the total approach volume at the signalized intersections in comparable models.

At signalized intersections, left- and right-turn bays were provided for all approaches. These bays extended 250-ft from the signal heads on the mainline and 200-ft from the signal heads on the side streets. Corner driveways (in all applicable models) were created at a spacing of 150-ft from the intersection. This distance was constrained due to the minimum distance of 100-ft required by VISSIM for a vehicle to make the required lane change based on a routing decision *(21)* and the length of turning bays. As described for the base model, if the VISSIM connectors for the turning bays overlap with the driveway movement connectors, the overlapping priority rules create confusion for the intersection and driveway turning traffic which results in vehicles following inappropriate (unrealistic) routes. This consideration was taken in development of all the models to minimize the number of vehicles unable to follow the designated route due to short (100-ft or less) distances from their current location to the next routing decision marker. For all the models, input traffic volumes and their assigned routes were checked against the output volumes produced by VISSIM and adjustments in the location of routing decisions were made where necessary. In addition, for corner driveways located on the approach side, the full-access designation excludes the left-in movement due to its direct conflict with the approaching left-turn traffic at the signalized intersection.

All driveways in the theoretical models had 1-lane each for inbound and outbound traffic, with 150-ft throat depth to provide adequate space for queuing vehicles. The modeling of two-way left-turn lanes was done using priority rules as previously described. All other parameters including vehicle and speed distributions were carried over from the base model. The models generated cars and heavy vehicles with relative flows of 98 and 2 percent respectively.

All theoretical models were simulated for 70 real-time minutes with the initial 10 minutes allowed to fill the network. The simulation resolution was set at 5 per simulation second, and the simulation speed was set at 10 simulated seconds for every real-time second. Each model was run three times with a different random seed to provide a distribution of output values. Each run for every model was visually checked for apparent errors and smooth operations especially for the TWLTL. In addition, error logs produced by VISSIM were checked for each run. While most of the 426 runs (142 times 3) were error-free, in a few models some vehicles were unable to find the designated route and were automatically removed from the simulation after 60-seconds of route searching. The maximum number of vehicles that experienced this issue was six out of more than 9000 vehicles generated in the analysis hour.

Figures 5.1 through 5.7 are the corridors for the 17 basic models with driveways (excluding volume distributions). Driveway spacing and additional volume considerations for these models are described as follows.

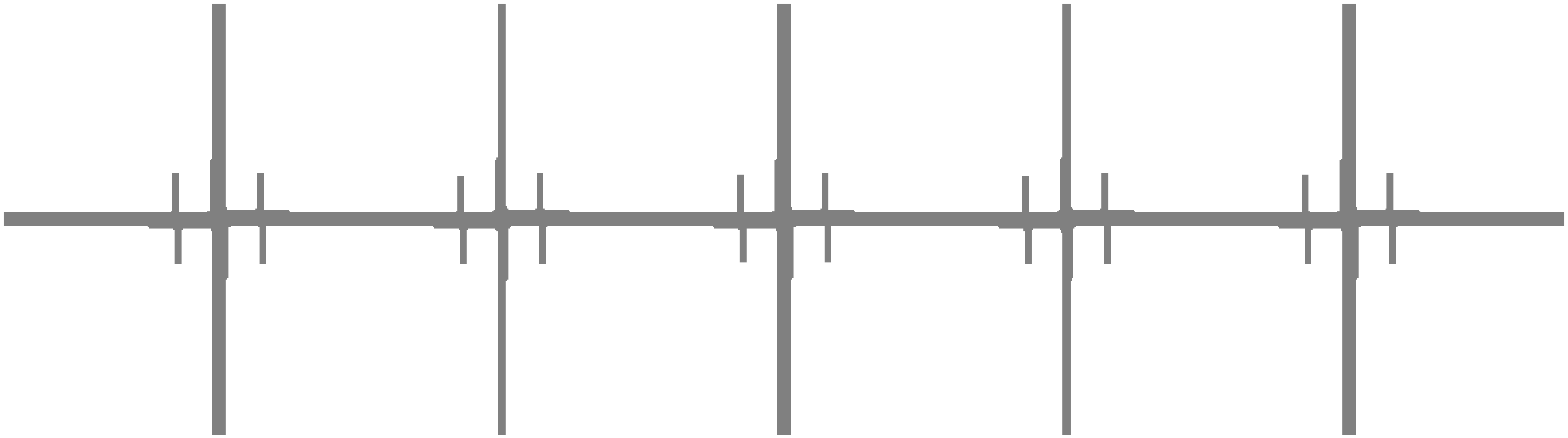

Figure 5.1 Cases C20-FA and C20-RR

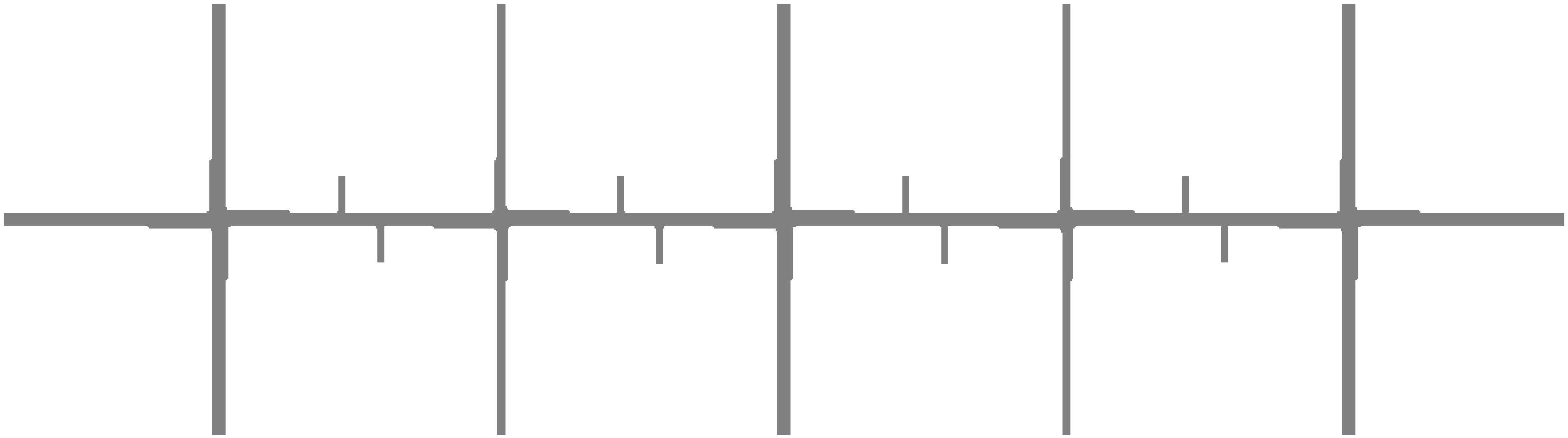

Figure 5.2 Cases M8-FA and M8-RR

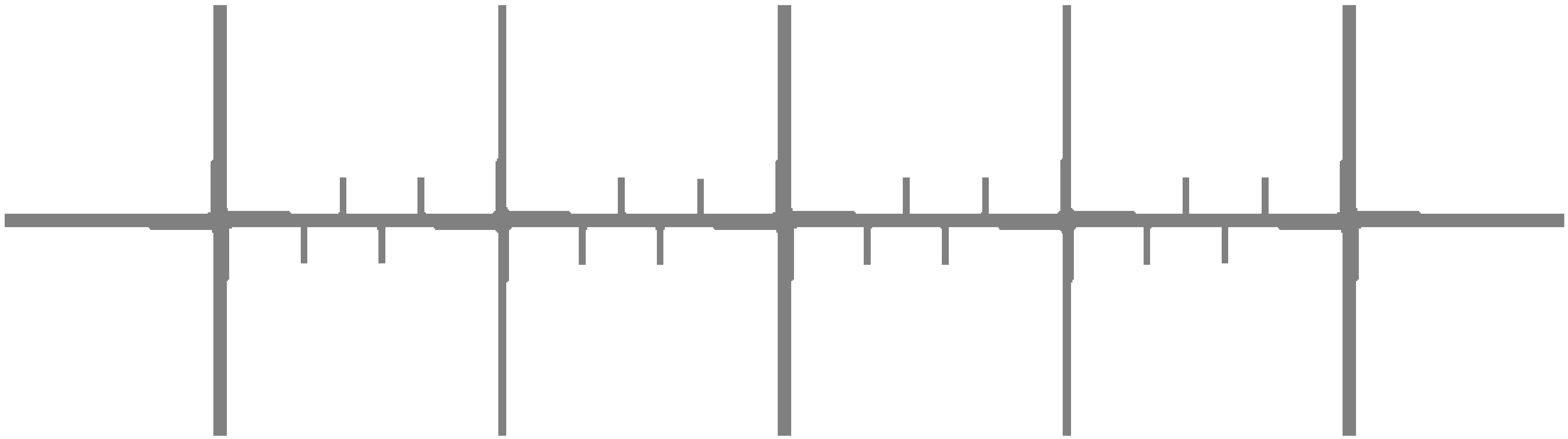

Figure 5.3 Cases M16-FA and M16-RR

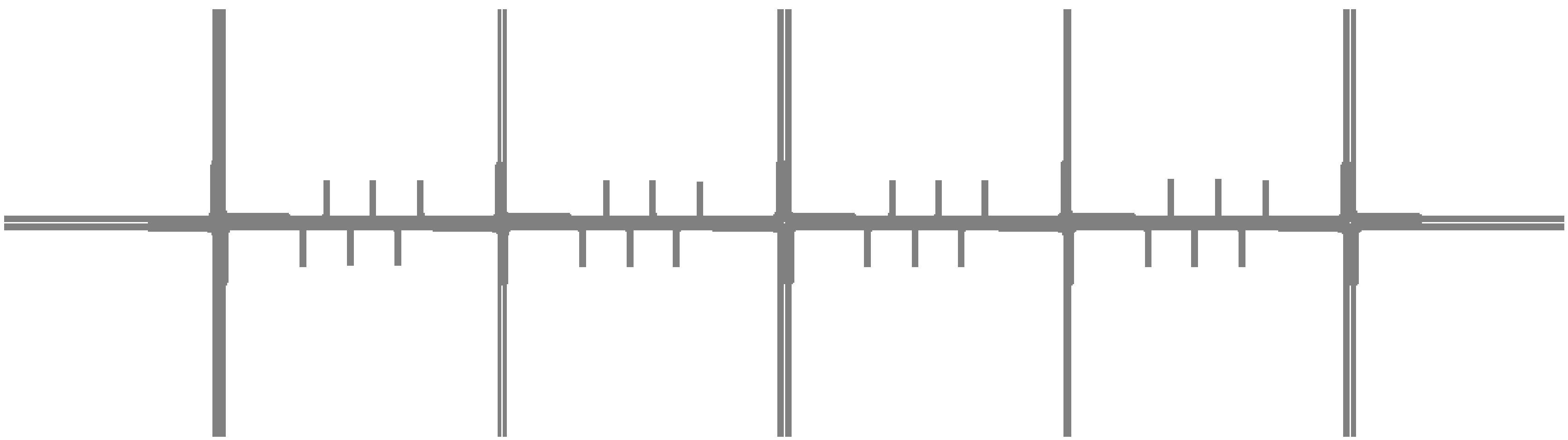

Figure 5.4 Cases M24-FA and M24-RR

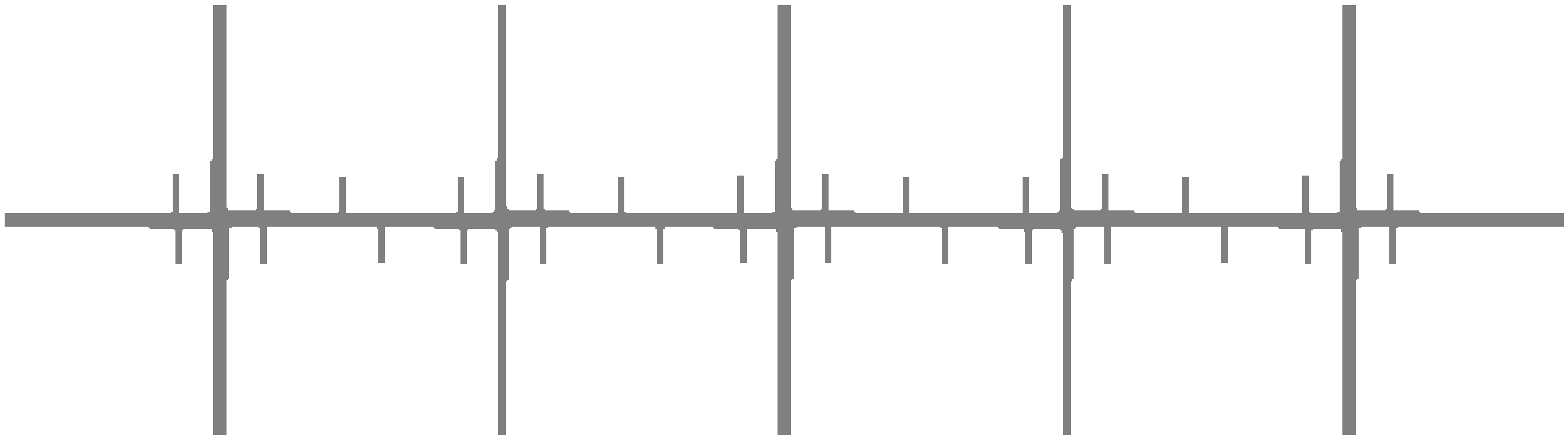

Figure 5.5 Cases C20-M8-FA, C20-M8-RR, and C20/RR-M8/FA

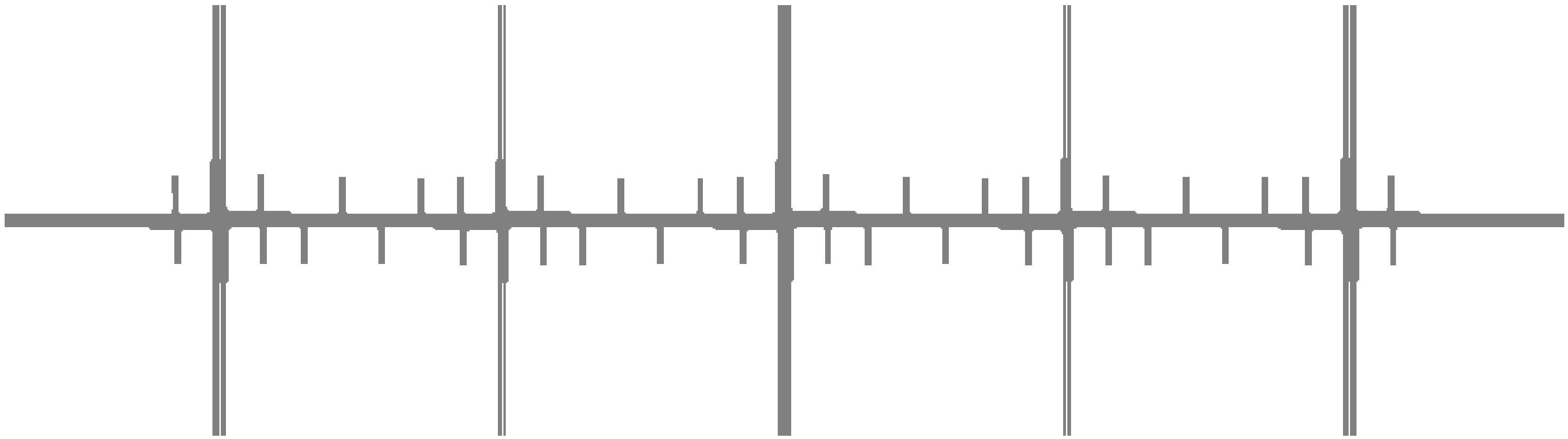

Figure 5.6 Cases C20-M16-FA, C20-M16-RR, and C20/RR-M16/FA

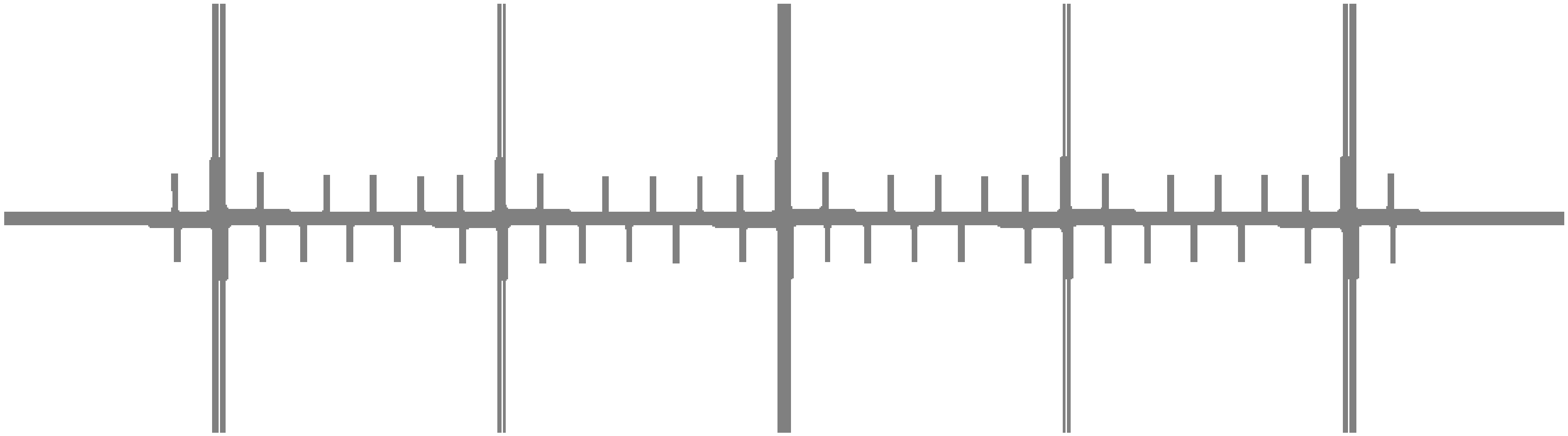

Figure 5.7 Cases C20-M24-FA, C20-M24-RR, and C20/RR-M24/FA

Figure 5.1 shows the basic VISSIM corridor for cases C20-FA and C20-RR, which includes 20 corner driveways in the corridor. To change access from full access to right-in/out only, in- and outbound driveway volumes and routes were altered. Three levels of mainline volumes (1500 vph, 1700 vph, and 1900 vph in each direction) were input for each case. In order to determine the driveway volume in each case that will result in excessive driveway delay and corresponding level of service 'F' (≥ 50 s/veh), driveway volumes were tested iteratively and then traffic volumes were adjusted in the entire corridor for a uniform directional distribution (i.e., equal traffic volume from each direction to/from the corridor). From the upper limits on driveway volume that results in forced-flow conditions, the driveway volumes were incrementally reduced until they produced delays at level of service 'A' (≤10 s/veh). This exercise resulted in the determination of minimum and maximum driveway volumes that needed to be modeled in VISSIM to determine operational impacts. This logic was used to determine driveway volume limits and to balance corridor-wide traffic in all theoretical models. For cases 'C20-FA' and 'C20-RR', 18 combinations of mainline and driveway volumes were modeled as shown in table 5.1.

Figure 5.2 shows the corridor with eight midblock driveways modeled as either full access or right-in/out. The driveways are offset at approximately 150-ft and are located mid-way between the signalized intersections in each segment. Figure 5.3 shows the corridor with 16 midblock driveways with offset spacing of approximately 150-ft, and figure 5.4 shows the corridor with 24 midblock driveways with offset spacing of approximately 85-ft. The combinations of access control, mainline volume, and driveway volumes modeled are shown in table 5.1.

Figures 5.5 through 5.7 show cases where all corner driveways are modeled and midblock driveways vary incrementally from eight per corridor to 24 per corridor with varying access control and volume scenarios (detailed in table 5.1).

5.4 Data Collection and Measures of Effectiveness

All theoretical models in VISSIM were set up to collect data for one hour during each of the three simulation runs. Several data collection methods were configured including corridor evaluation, intersection evaluation, and individual data collection points for all driveways and TWLTL movements in each model.

For corridor performance evaluation, the data collected during each simulation time-step were aggregated into hourly values for each run. The following variables were computed: number of vehicles in the corridor, total travel time for all vehicles (hours), total delay for all vehicles (hours), average speed for all vehicles (mph), average delay per vehicle (s/veh), average number of stops per vehicle, and average stop delay per vehicle (s/veh).

For intersection evaluation, nodes were defined for all five intersections that included the entire lengths of the turning bays. At each signalized intersection, the following variables were computed: overall intersection level of service; average delay (s/veh) for the intersection overall, by approach, and by movement; intersection volume (vph) for the intersection, by approach, and by movement; and, average and 95th percentile queue length (ft) by approach and by movement.

Data collection points were defined in each model and included each driveway’s in- and out-bound movement as well as movements in the TWLTL. The following were collected at each station: number of vehicles, average delay (s/veh) by movement, stop delay (s/veh) by movement, number of stops, average queue delay (sec), and maximum queue delay (sec).

For a given model, VISSIM creates data outputs for each run in multiple formats including six files in text format, one Microsoft Access database file, and one Microsoft Excel file. This resulted in 24 output files for each model, and 3,408 total files for all theoretical models. In order to systematically compile data for analysis, a ‘data transfer template’ was created in Excel which was programmed to read data from multiple source files, aggregate time-step data into hourly estimates, and included a check for standard deviation between variables from the three runs to flag outliers. This data for each model were then transferred to another Excel ‘output template’ that was programmed to compile data for all corner driveways, all midblock driveways, TWLTL data, intersection data, and corridor data. For each volume input in every model, the ‘output template’ also computed the percentage difference between movement-specific volume input and stochastically-generated total volume output within the analysis hour. It was found that for almost all the cases, the percentage difference was within ±1%. For some cases (~15) where high driveway volumes were combined with high mainline volumes, the percentage difference increased up to ±6% due to congestion in the system that restricted the desired number of vehicles to pass a particular data collection point. The compilers created for this research significantly increased the efficiency of assembling data for further analysis.

Given the number of theoretical models and the large number of corresponding variables generated at each analysis level, average delay (s/veh) is selected as the primary MOE for a detailed comparison of operational evaluation as described in chapter 6. Other corridor-wide and driveway-specific MOEs are presented where needed and detailed results are provided in appendices.

CHAPTER 6

OPERATIONAL EVALUATION OF THEORETICAL MODELS

6.1 Introduction

The operational evaluation is performed using the VISSIM simulation software output for each theoretical case modeled in order to determine the quantitative effects of varying mainline volume, driveway volume, driveway density, access restrictions, and a combination of these factors on 5-lane highways (table 5.1). The comparative analysis is carried out at three levels for each model: corridor-wide, signalized intersections, and at driveways including operations at the TWLTL as described below.

6.2 Evaluation of Theoretical Models at the Corridor Level

For operational evaluation at the corridor level, the following variables were aggregated for the analysis hour in each theoretical model: total volume simulated in an hour, total travel time of all vehicles (hours), total delay of all vehicles (hours), average speed (mph), average delay per vehicle (s/veh), and average stop delay (s/veh). For each of the three mainline volumes (1500, 1700, and 1900 vph per direction), a baseline case was also modeled without any driveways. First, an overall comparison between all cases for each of the three mainline volumes is presented. Then, cases-by-case corridor-level comparison of MOEs is presented to evaluate the impact of varying access density, location, type, and volume.

As noted before, signalized intersection timings were optimized for each of the three baseline cases and input in VISSIM. Tables 6.1 through 6.3 show the corridor-wide MOEs including volume simulated, average delay, and average speed for each case and its respective driveway volume. (Additional results including travel time and average stop delay are shown in appendix A.) The driveway volumes represent the total inbound and outbound volume for each driveway. For example, in case C20-FA (20 full-access corner driveways), the driveway volume 50 (vehicles per hour per driveway, vphpd) represents 25 inbound vehicles and 25 outbound vehicles.

The common comparison factor for corridor-level evaluation across all models is the total volume simulated which varies from 2.7% to 28.0% from the baseline. As indicated in tables 6.2 and 6.3, six of the 142 combinations experienced congested conditions in the initial stages of the simulation runs resulting in a lack of usable results due to VISSIM's inability to process the required number of vehicles in the analysis hour. These cases, marked as 'system breakdown,' include: M24-FA (at 150 and 200 vphpd) for medium mainline volume; and for high mainline volume, M24-FA (at 100 and 200 vphpd), C20-M24-FA (at 25 vphpd corner/150 vphpd midblock), and C20/RR-M24/FA (at 150 vphpd). The total number of cases with valid results is 133 in addition to the three baseline cases.

The following are the overall results for cases modeled with low mainline volume.

- For the 47 cases modeled with low mainline volume (1500 vph), the increase in the total simulated volume from the baseline ranged from 4.7% (cases M8-FA and M8-RR at 100 vphpd) to 28.0% (case C20-M24-FA at 150 vphpd).
- The minimum increase of 0.8% in the total travel time (hours) was recorded for case C20-FA (at 50 vphpd), and the maximum increase was 9.8% for case C20-M24-FA (at 150 vphpd).

- The increase in average delay (s/veh) ranged from 6.0% (case M8-RR at 100 vphpd) to 37.2% (C20-M24-FA at 150 vphpd).
- The minimum reduction of 0.4% in average speed (mph) was recorded for case M8-RR (at 100 vphpd), and the maximum reduction of 6.6% occurred for case C20-M24-FA (at 150 vphpd). These cases and corresponding values of the MOEs are shown in table 6.1.

Table 6.1 Corridor-wide MOEs for Low Mainline Volume Models

Case	Low Mainline Volume (1500 vph)			
	Driveway Volume (vphpd)	**Volume Simulated (vph)**	**Average Delay (s/veh)**	**Average Speed (mph)**
Baseline	0	8763	50.85	21.45
C20-FA	50	9299	51.65	21.29
	100	9805	52.08	21.18
	150	10321	54.28	20.86
C20-RR	50	9305	51.53	21.34
	100	9810	51.84	21.23
	150	10303	54.31	20.97
M8-FA	100	9195	51.80	21.33
	200	9581	52.49	21.20
M16-FA	100	9603	52.61	21.17
	200	10399	54.11	20.91
M24-FA	100	9979	54.54	20.91
	150	10638	56.21	20.67
	200	11215	57.29	20.44
M8-RR	100	9200	51.53	21.37
	200	9585	51.82	21.32
M16-RR	100	9606	52.14	21.29
	200	10401	53.24	21.12
M24-RR	100	9977	53.61	21.09
	200	11205	55.94	20.72
C20-M8-FA	50	9495	51.99	21.23
	100	10211	53.12	21.03
	150	10939	55.53	20.66
C20-M16-FA	50	9624	52.28	21.18
	100	10619	53.93	20.90
	150	11566	56.84	20.41
C20-M24-FA	50	9920	53.93	20.99
	100	11001	55.84	20.63
	150	12160	58.37	20.12
C20-M8-RR	50	9496	51.64	21.33
	100	10213	52.89	21.12
	150	10935	55.93	20.83

Table 6.1 Cont'd

Case	Low Mainline Volume (1500 vph)			
	Driveway Volume (vphpd)	**Volume Simulated (vph)**	**Average Delay (s/veh)**	**Average Speed (mph)**
C20-M16-RR	50	9719	51.96	21.29
	100	10624	53.17	21.08
	150	11514	55.69	20.75
C20-M24-RR	50	9913	53.32	21.14
	100	11004	55.14	20.81
	150	12108	56.98	20.49
C20/RR-M8/FA	50	9496	51.79	21.30
	100	10218	53.03	21.10
	150	10944	54.91	20.86
C20/RR-M16/FA	50	9721	52.30	21.21
	100	10625	53.65	20.98
	150	11556	56.38	20.60
C20/RR-M24/FA	50	9910	53.76	21.06
	100	11003	55.50	20.73
	150	12115	57.62	20.33

The following are the overall results for cases modeled with medium mainline volume.

- For the 45 cases modeled with medium mainline volume (1700 vph), the increase in the total simulated volume from baseline ranged from 3.2% (cases C20-FA at 25 vphpd) to 27.1% (case C20/RR-M24/FA at 150 vphpd).
- The minimum increase of 0.75% in the total travel time (hours) was recorded for case C20-RR (at 50 vphpd), and the maximum increase was 12.9% for case C20/RR-M24/FA (at 150 vphpd).
- The increase in average delay (s/veh) ranged from 6.0% (case M8-RR at 100 vphpd) to 39.2% (C20/RR-M24/FA at 150 vphpd).
- The minimum reduction of 0.3% in average speed (mph) was recorded for case M8-RR (at 100 vphpd), and the maximum reduction of 9.8% occurred for case C20/RR-M24/FA (at 150 vphpd). These cases and corresponding values of MOEs are shown in table 6.2.

Table 6.2 Corridor-wide MOEs for Medium Mainline Volume Models

Case	Medium Mainline Volume (1700 vph)			
	Driveway Volume (vphpd)	**Volume Simulated (vph)**	**Average Delay (s/veh)**	**Average Speed (mph)**
Baseline	0	9155	59.50	20.31
C20-FA	25	9461	62.41	20.01
	50	9701	62.40	20.01
	100	10190	64.12	19.53
C20-RR	50	9704	60.21	20.23
	100	10214	60.27	20.18
	150	10704	63.84	19.80
M8-FA	100	9597	60.96	20.14
	200	9973	62.20	19.95
M16-FA	100	10003	62.07	19.97
	200	10803	64.50	19.58
M24-FA	100	10378	66.17	19.38
	150	system breakdown		
	200	system breakdown		
M8-RR	100	9604	60.37	20.24
	200	10010	61.56	20.08
M16-RR	100	10012	61.32	20.11
	200	10798	63.60	19.76
M24-RR	100	10361	65.25	19.54
	200	11586	69.34	18.87
C20-M8-FA	50	9895	61.38	20.02
	100	10612	64.95	19.43
	25 (corner), 150 (midblock)	10078	63.29	19.82
C20-M16-FA	50	10116	62.09	19.91
	100	11004	66.09	19.24
	25 (corner), 150 (midblock)	10699	65.82	19.47
C20-M24-FA	50	10314	66.65	19.24
	100	11381	70.53	18.53
	25 (corner), 150 (midblock)	11278	70.35	18.66

Table 6.2 Cont'd

Case	Medium Mainline Volume (1700 vph)			
	Driveway Volume (vphpd)	**Volume Simulated (vph)**	**Average Delay (s/veh)**	**Average Speed (mph)**
C20-M8-RR	50	9898	60.44	20.20
	100	10620	61.44	20.06
	150	11318	65.53	19.64
C20-M16-RR	50	10116	60.82	20.17
	100	11024	62.39	19.92
	150	11930	66.67	19.38
C20-M24-RR	50	10309	64.50	19.66
	100	11394	66.89	19.26
	150	12495	69.82	18.79
C20/RR-M8/FA	50	9898	60.32	20.22
	100	10618	61.97	19.99
	150	11347	64.92	19.64
C20/RR-M16/FA	50	10120	61.26	20.09
	100	11025	63.01	19.81
	150	11956	67.05	19.29
C20/RR-M24/FA	50	10300	65.36	19.51
	100	11398	67.78	19.08
	150	12559	71.33	18.50

The following are the overall results for cases modeled with high mainline volume.

- For the 44 cases modeled with high mainline volume (1900 vph), the increase in the total simulated volume from baseline ranged from 2.7% (cases M8-FA at 50 vphpd) to 26.0% (case C20-M24-RR at 150 vphpd).
- The minimum increase of 0.6% in the total travel time (hours) was recorded for case C20-RR (at 50 vphpd), and the maximum increase was 21.3% for case C20-M24-FA (at 100 vphpd).
- The increase in average delay (s/veh) ranged from 6.4% (case C20-RR at 50 vphpd) to 41.6% (C20-M24-RR at 150 vphpd).
- The minimum reduction of 0.1% in average speed (mph) was recorded for case C20-M8-RR (at 100 vphpd), and the maximum reduction of 26.4% occurred for case C20-M24-FA (at 100 vphpd). These cases and corresponding values of MOEs are shown in table 6.3.

Overall, the corridor-wide results indicate that given a comparable increase in the total network volume due to the addition of driveways, increasing mainline volume has a significant impact on travel times, delays, and average speeds. When mainline volume was increased from 1500 vph (per direction) to 1700 vph, the travel time increased by up to 3.1%, whereas an increase from 1700 vph to 1900 vph resulted in an increase of up to 8.4%. The average speed was reduced in a similar fashion, with approximately 4.0% reduction from low- to medium mainline volume, and up to 16.5% reduction from medium- to high mainline volume cases. Case-by-case comparisons are provided next.

Table 6.3 Corridor-wide MOEs for High Mainline Volume Models

Case	High Mainline Volume (1900 vph)			
	Driveway Volume (vphpd)	Volume Simulated (vph)	Average Delay (s/veh)	Average Speed (mph)
Baseline	0	9539	70.29	19.07
C20-FA	25	9853	76.67	18.33
	50	10061	77.09	18.08
	100	10506	81.50	17.35
C20-RR	50	10100	70.90	19.02
	100	10590	71.81	18.86
	150	11089	77.46	18.24
M8-FA	50	9803	74.77	18.64
	100	9983	72.67	18.81
	200	10350	75.83	18.35
M16-FA	100	10396	74.80	18.52
	200	11190	80.92	17.61
M24-FA	50	10172	83.99	17.23
	100	system breakdown		
	200	system breakdown		
M8-RR	100	9986	71.90	18.92
	200	10377	74.73	18.53
M16-RR	100	10400	73.88	18.67
	200	11196	78.62	17.99
M24-RR	100	10740	83.29	17.32
	200	11973	89.28	16.36
C20-M8-FA	50	10268	76.98	18.11
	100	10872	83.95	16.98
	25 (corner), 150 (midblock)	10433	79.72	17.82
C20-M16-FA	50	10488	78.17	17.95
	100	11295	85.73	16.70
	25 (corner), 150 (midblock)	11070	83.31	17.33

Table 6.3 Cont'd

Case	High Mainline Volume (1900 vph)			
	Driveway Volume (vphpd)	**Volume Simulated (vph)**	**Average Delay (s/veh)**	**Average Speed (mph)**
C20-M24-FA	50	10654	87.17	16.60
	100	11547	94.68	15.09
	25 (corner), 150 (midblock)	system breakdown		
C20-M8-RR	50	10293	70.82	19.04
	100	10996	73.54	18.69
	150	11683	81.63	17.72
C20-M16-RR	50	10516	73.17	18.75
	100	11404	76.25	18.31
	150	12301	83.17	17.42
C20-M24-RR	50	10596	81.56	17.51
	100	11737	84.49	17.11
	150	12885	89.09	16.42
C20/RR-M8/FA	50	10298	72.10	18.88
	100	10997	74.27	18.59
	150	11727	81.29	17.68
C20/RR-M16/FA	50	10515	73.64	18.67
	100	11404	76.47	18.26
	150	12336	84.55	17.18
C20/RR-M24/FA	50	10667	83.42	17.27
	100	11765	87.44	16.62
	150	system breakdown		

Figures 6.1 to 6.10 show the corridor-wide percent differences in average delay and average speed against the hourly corridor volume for all cases. In all the figures shown in this chapter, cases with full-access driveways and mixed driveways (i.e., corner right-in/out and midblock full-access) are shown with continuous lines, whereas cases with only right-in/out driveways are shown with dashed lines. Figures for corridor evaluation are organized as described below.

- The first set (figures 6.1 and 6.2) shows corridor-wide MOEs for cases with corner driveways only including C20-FA and C20-RR.
- The next set (figures 6.3 and 6.4) shows results for all midblock-only driveway cases including M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR.
- Figures 6.5 and 6.6 show results for cases C20-M8-FA, C20-M16-FA, and C20-M24-FA.
- Figures 6.7 and 6.8 show results for cases C20-M8-RR, C20-M16-RR, and C20-M24-RR.
- Figures 6.9 and 6.10 show results for cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA.

In addition to the figures, tables summarizing data for difference in total delay from the baseline for each set are also shown. Actual values of the MOEs are presented in tables 6.1 to 6.3 and additional data for each case are provided in the appendices. Discussion of results is provided separately for each set of cases.

6.2.1 Corridor-wide Evaluation of Cases C20-FA and C20-RR

Figure 6.1 and table 6.4 show the difference in corridor-wide average delay per vehicle for cases where only corner driveways were modeled at 150-ft from the signalized intersection. For full-access driveways on the approach side, no left-in movements were allowed in any corner driveway (in all cases) due to the absence of a dedicated TWLTL. However, left-out movements were modeled in such a way that a vehicle waiting in the driveway to turn left must merge directly into the through traffic only when minimum gap time is available to clear all potential conflicts. The data indicates an increase in average delay with corresponding increase in mainline volume especially with full-access driveways. The average delays for right-in/out cases were lower than full-access delays for a given driveway volume as well as mainline volume. At 25 vphpd for full-access, the delay increased by approximately 3.5% from medium to high mainline volume. At 50 vphpd for full-access, the delay increased by approximately 2.8% from low to medium mainline volume, and by approximately 3.6% from medium to high mainline volume. At 100 vphpd for full-access, the delay increased by 4.5% from low to medium mainline volume, and by 5.1% from medium to high mainline volume. Also for full-access cases, the mainline volume seems to have a more significant impact on the delay compared to driveway volume. Additional comparison of difference in delays from baseline and between specific cases by mainline volume, driveway volume, and access type can be made from results in table 6.4.

An overall increase in the travel time (figure A.1) with was also observed with increasing mainline volume as well as with increasing driveway volume especially for full-access cases. At 25 and 50 vphpd for full-access cases, the travel time increased on an average by 2.0% with increasing mainline volume. At high driveway volume (100 vphpd), the travel time increased by approximately 3.0% and 4.0% with mainline volume increase to 1700 vph and 1900 vph respectively. For the right-in/out cases for all mainline volume levels, the travel time increased more rapidly when increasing driveway volume from 100 to 150 vphpd (3.0% to 5.0% increase) compared to a change from 50 to 100 vphpd (<1.0% increase across all mainline volumes). Also, the difference in travel time with increasing mainline volume is noted only at the high driveway volume (150 vphpd) for right-in/out cases, with an average increase of approximately 1.7% from low to high mainline volume.

Table 6.4 Corridor-wide Difference in Average Delay for Cases C20-FA and C20-RR

Mainline Volume (vph)	Driveway Volume (vphpd)	Case	
		C20-FA	**C20-RR**
1500	50	7.2%	7.1%
	100	12.7%	12.4%
	150	20.5%	20.4%
1700	25	7.7%	n/a
	50	10.0%	6.8%
	100	16.6%	11.5%
	150	n/a	20.3%
1900	25	11.2%	n/a
	50	13.6%	6.4%
	100	21.7%	11.8%
	150	n/a	21.9%

From figure 6.2, the differences in average speeds (mph) follow similar overall trends (albeit in reverse direction) as observed for travel times and delays. The highest reduction in average speed at approximately 10.0% is shown for the full-access case at high mainline volume with 100 vphpd. Average speeds for right-in/out cases were higher than corresponding full-access cases. Again, the impact of increasing mainline volume seems to have a larger impact in reducing average speeds compared to increasing driveway volumes especially for full-access cases.

For the cases C20-FA (20 full-access corner driveways) and C20-RR (20 right-in/out corner driveways), the following overarching observations and conclusions are made at the corridor-level.

- The travel time and total delay were higher, and the average speeds were lower for all full-access (C20-FA) cases compared to all right/in-out (C20-RR) cases.
- Adding full-access driveways at 150-ft from the intersection at all corners on the mainline resulted in an increased average delay from 7.2% (at 50 vphpd at 1500 vph mainline volume) to 21.7% (at 100 vphpd at 1900 vph mainline volume) (figure 6.1). The corresponding reduction in average speed (mph) ranged from 1.0% to about 10.0% (figure 6.2).
- Adding right-in/out driveways at 150-ft from the intersection at all corners on the mainline resulted in an increased delay from 7.1% (at 50 vphpd at 1500 vph mainline volume) to 21.9% (at 150 vphpd at 1900 vph mainline volume) (figure 6.1). The corresponding reduction in average speed (mph) ranged from 0.5% to about 4.5% (figure 6.2).
- The deterioration in corridor-wide MOEs was more significant with increasing mainline volume compared to increasing driveway volume especially with full-access driveways. For right-in/out driveways, the total delay increased by about 1.5% for up to 100 vphpd when increasing mainline volume from low to high, but the delay increased by more than 5.0% when driveway volumes were increased from 100 to 150 vphpd across all mainline volume levels.

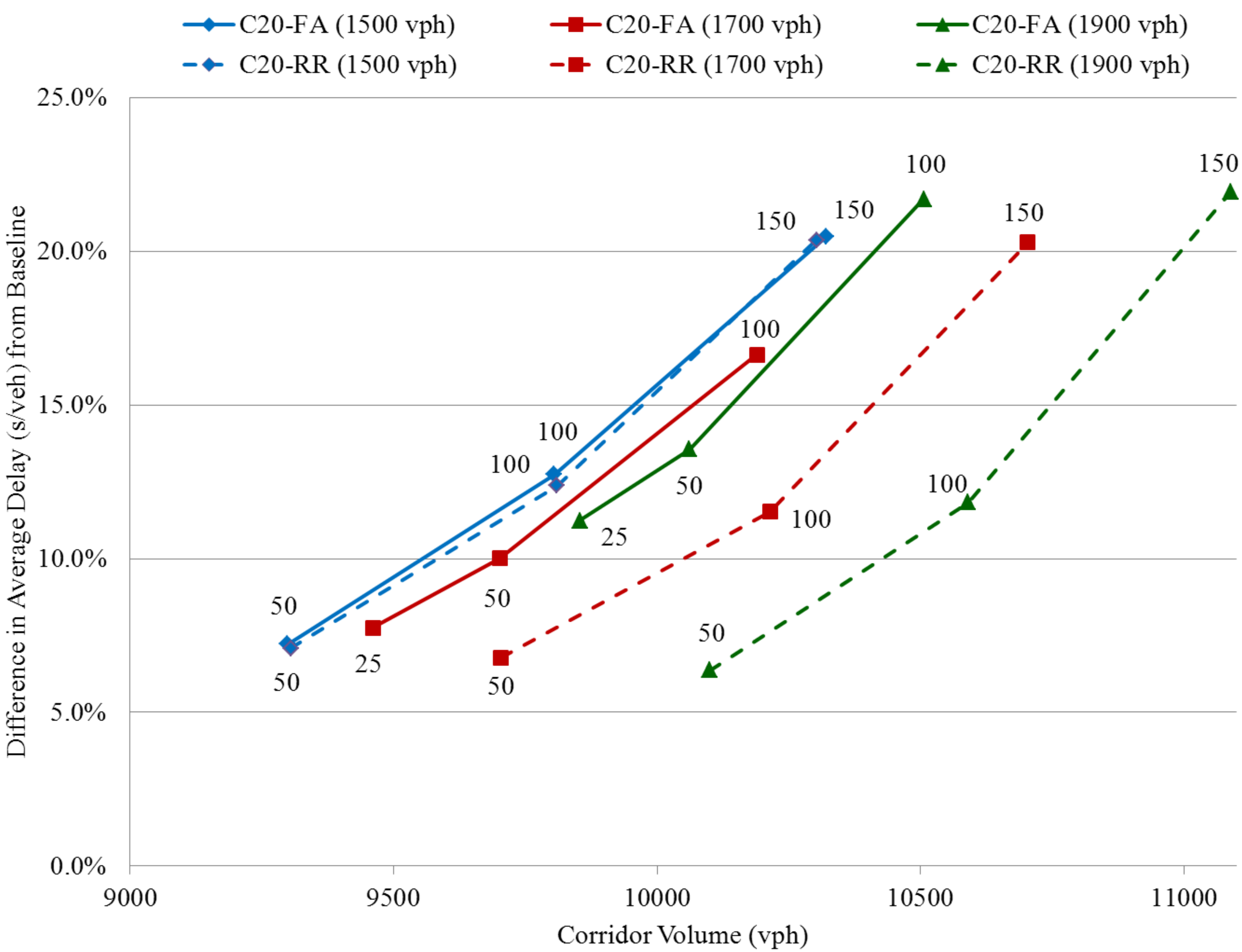

Figure 6.1 Corridor-wide Difference in Average Delay for Cases C20-FA and C20-RR

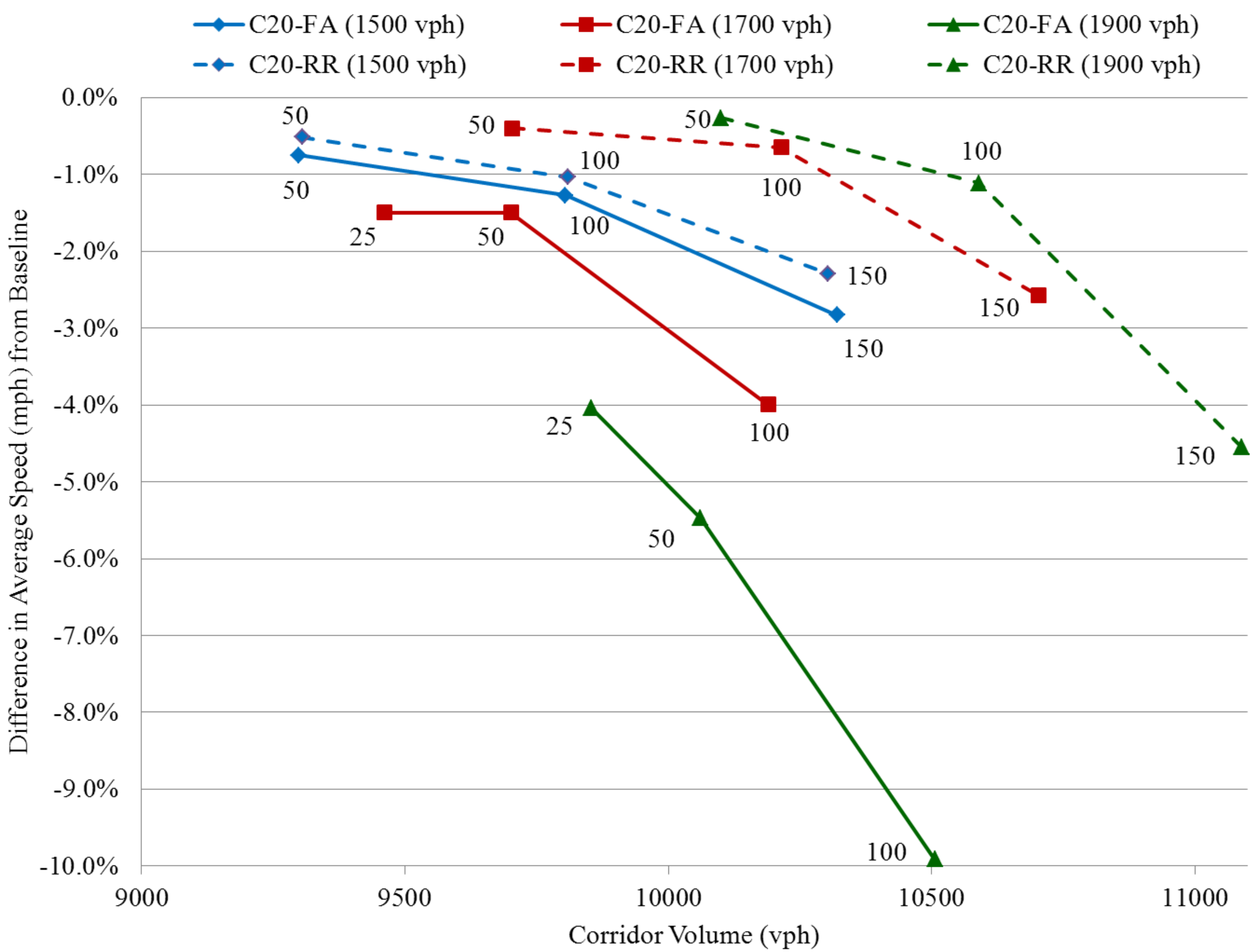

Figure 6.2 Corridor-wide Difference in Average Speed for Cases C20-FA and C20-RR

6.2.2 Corridor-wide Evaluation of Cases M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR

Figures 6.3 and 6.4 show corridor-wide differences in average delay and average speed for all cases with full-access (FA) and right-in/out (RR) driveways only at midblock (M) locations varying between 8 and 24 driveways per mile. As noted before for case M24-FA, only one data point each is plotted at 100 vphpd for medium mainline volume and at 50 vphpd for high mainline volume due to system breakdown at higher driveway volumes.

Figure 6.3 and table 6.5 show the difference in corridor-wide average delay per vehicle from the baseline for all midblock cases. Average delays for full-access cases were consistently higher than right-in/out cases for all driveway volumes, although the difference in delays increased for a given driveway volume between full-access and right-in/out cases with an increase in mainline volume. The highest average delay increase of 37.3% was observed for M24-RR at 200 vphpd with high mainline volume.

Table 6.5 Corridor-wide Difference in Average Delay for Cases M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR

Mainline Volume (vph)	Driveway Volume (vphpd)	Case					
		M8-FA	M8-RR	M16-FA	M16-RR	M24-FA	M24-RR
1500	100	6.4%	6.0%	11.8%	11.0%	18.1%	16.7%
	150	n/a				25.5%	n/a
	200	11.4%	10.3%	20.8%	19.5%	30.6%	28.9%
1700	100	6.9%	6.0%	12.3%	11.3%	20.7%	19.4%
	150	n/a				breakdown	n/a
	200	12.2%	11.6%	21.8%	20.7%		32.2%
1900	50	8.5%	n/a			21.5%	n/a
	100	7.6%	6.6%	13.8%	12.7%	breakdown	25.0%
	200	14.6%	13.5%	25.9%	23.8%		37.3%

The right-in/out cases showed approximately 2.0% or less overall total travel time compared to corresponding full-access cases at all driveway volumes (figure A.4). For all full-access and right-in/out cases with up to 16 midblock driveways in the corridor, the difference in travel time from baseline (no driveways) was <5.0% under low and medium mainline volumes. At high mainline volume with 16 midblock driveways, the difference increased up to 9.0% for full-access and 7.2% for right-in/out cases at 200 vphpd. These differences are similar to the case with 24 midblock driveways at low mainline volume at 200 vphpd (8.6% for full-access and 7.4% for right-in/out). In M24-FA at high mainline volume and 50 vphpd (only driveway volume for this case), the increase in travel time was 11.0% which is equivalent to M24-RR at high mainline volume and 100 vphpd. The maximum difference in travel time was observed at 17.0% for case M24-RR at 200 vphpd.

Reduction in the average speed of up to 5.0% is noted for a majority of midblock cases as shown in figure 6.4. A decrease of more than 5.0% in average speed occurred mostly for high mainline volume cases with an exception of M24-RR at medium mainline volume at 200 vphpd (7.6% reduction noted). At high mainline volumes with 24 midblock driveways, the average speed was reduced by more than 10.0% with full-access driveways at 50 vphpd as well as with right-in/out driveways at 100 vphpd. The largest reduction in average speed was for M24-RR at 200 vphpd with high mainline volume.

The following are the main observations and conclusions at the corridor-level for all cases with midblock driveways only.

- With high mainline volume conditions, adding 24 full-access driveways per mile increased the average delay by 21.5% at 50 vphpd, and decreased the average speed by more than 10.0% (figure 6.3).
- With 24 right-in/out driveways and high mainline volume, the average delay increased by more than 25.0% at 100 vphpd and increased by about 37.3% at 200 vphpd (figure 6.3). The average speeds reduced by more than 10.0% and 16.0% respectively (figure 6.4).
- At high midblock access density (24 full-access driveways), the corridors experienced highly congested conditions with medium as well at high mainline volume when driveway volumes exceeded 100 vphpd.

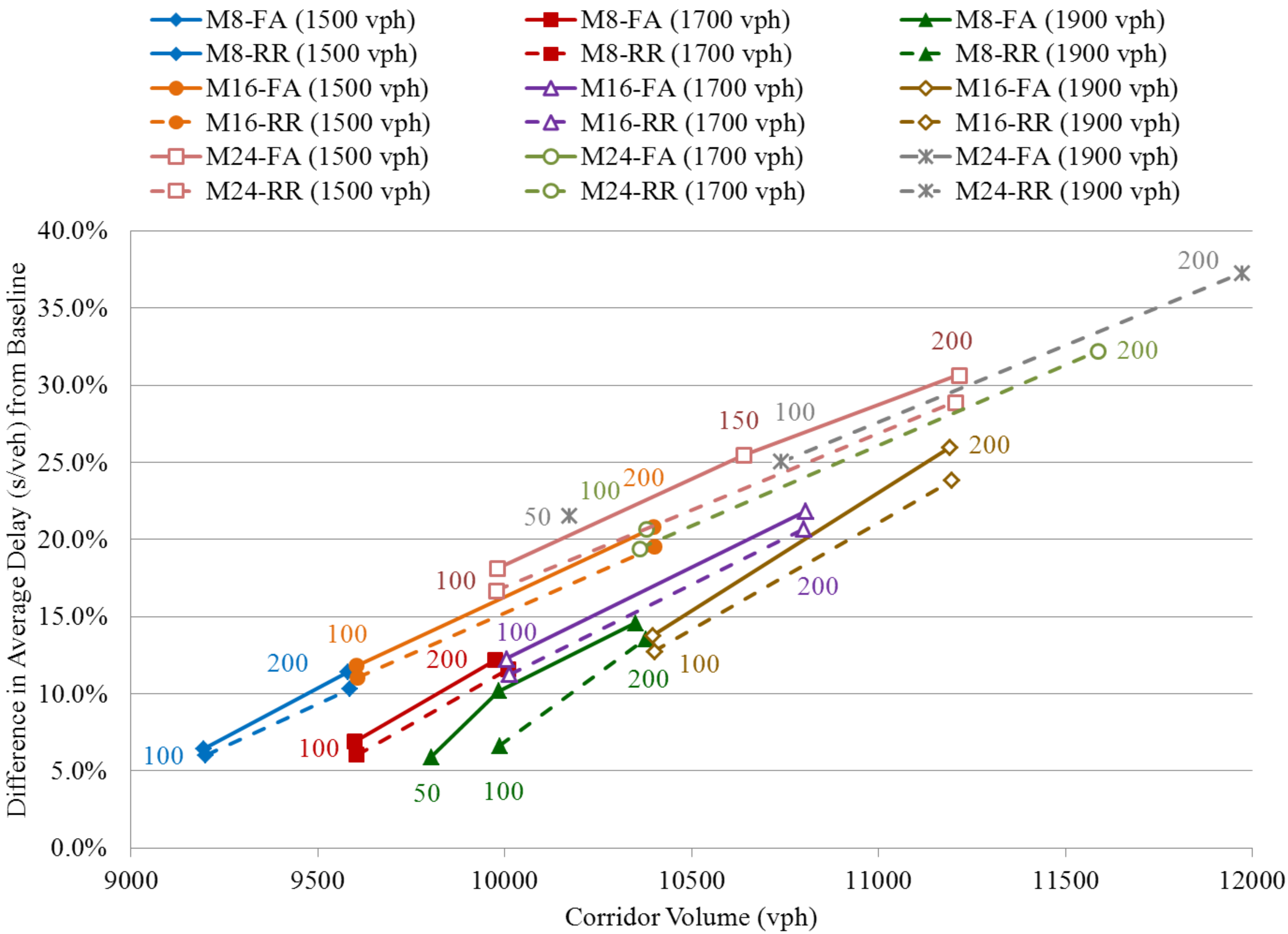

Figure 6.3 Corridor-wide Difference in Average Delay for Cases M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR

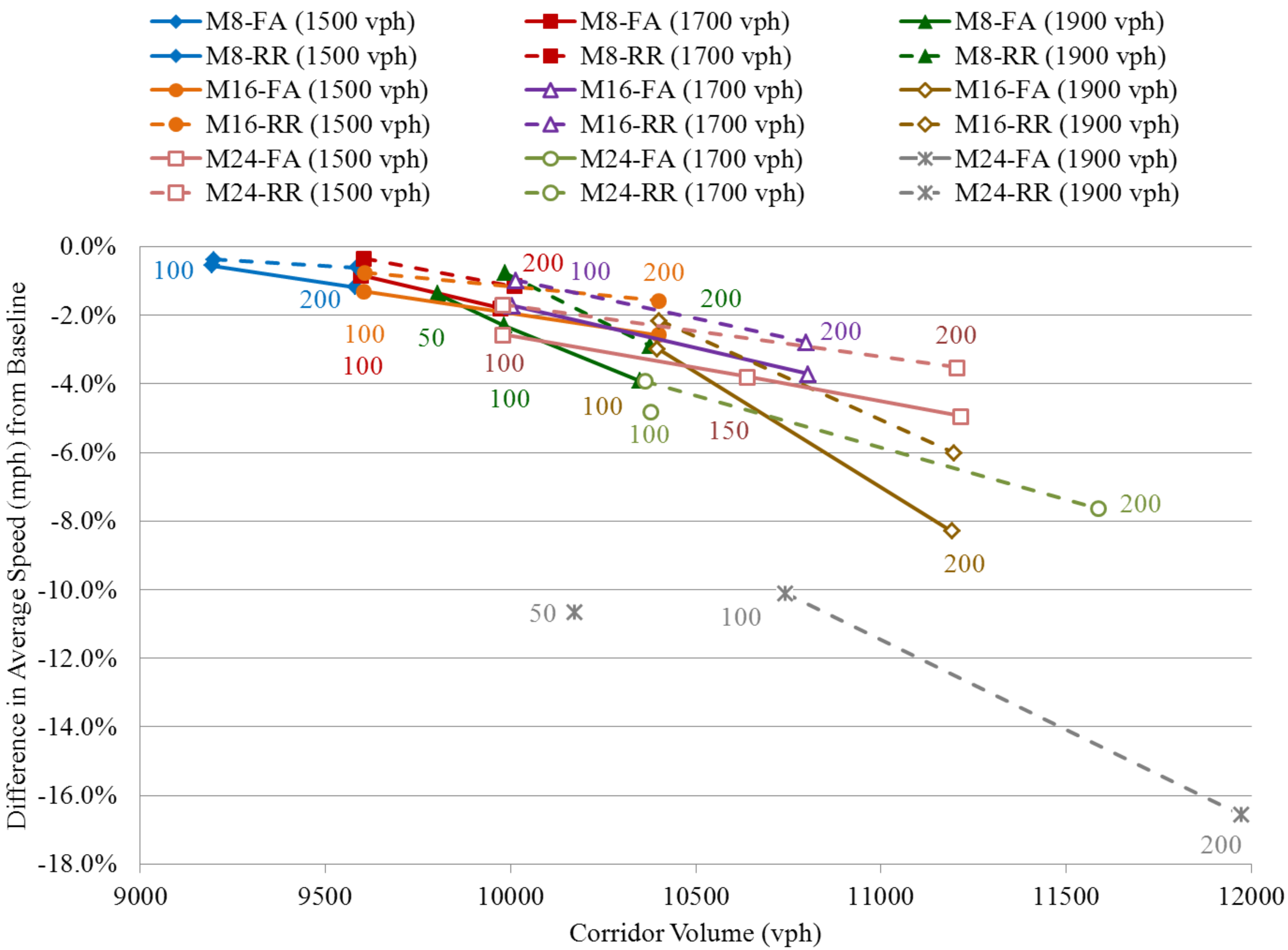

Figure 6.4 Corridor-wide Difference in Average Speed for Cases M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR

6.2.3 Corridor-wide Evaluation of Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

Figures 6.5 and 6.6 show corridor-wide MOEs for cases with 20 full-access (FA) corner (C) driveways and full-access (FA) midblock (M) driveways varying from 8 to 24 per mile. As shown in tables 6.2 and 6.3, at medium and high mainline volumes the driveway volumes modeled were 50 and 100 vphpd for both corner and midblock driveways, and a special case with corner driveways modeled at 25 vphpd and midblock driveways at 150 vphpd. The latter was done after the models with 150 vphpd for both corner and midblock driveways at medium and high mainline volumes experienced system breakdown. Also note that even with this driveway volume configuration (corner at 25 and midblock at 150 vphpd), simulation for case C20-M24-FA under high mainline volume experienced congested conditions in the initial stages and the expected number of vehicles could not be processed in the analysis hour.

In figure 6.5 and table 6.6, the difference in average delay per vehicle is shown for all cases with full-access corner and midblock driveways. For driveway volume of 50, with 8 midblock driveways the delay increased from 9.7% to 15.2% with increase in mainline volume from 1500 to 1900 vph. For the same driveway volume, with 16 midblock driveways the delay increased from 11.4% to 18.2% with increase in mainline volume from low to high. And with 24 midblock driveways, the increase in delay ranged from 16.7% to 27.8% with increase in mainline from low to high. Similar increases can be observed from table 6.6 which indicates that the average delay approximately doubled with increasing driveway volume from 50 to 100 vphpd across all driveway densities and also with increasing mainline volumes. The delays were lower for combination driveway volume cases (corner 25 and midblock 150 vphpd) than cases with 100 vphpd across all driveway densities and medium to high mainline volumes, although a wide range of differences is observed from 0.8% to 7.2%. The average delay increased more rapidly as the midblock driveway density increases from 16 to 24 compared to the increase from 8 to 16 especially at medium and high mainline volumes.

Table 6.6 Corridor-wide Difference in Average Delay for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

Mainline Volume (vph)	Driveway Volume (vphpd)	Case		
		C20-M8-FA	C20-M16-FA	C20-M24-FA
1500	50	9.7%	11.4%	16.7%
	100	17.8%	22.2%	27.5%
	150	26.6%	32.2%	37.2%
1700	50	10.3%	13.3%	20.8%
	100	21.0%	25.1%	32.1%
	25C, 150M	14.6%	22.6%	31.3%
1900	50	15.2%	18.2%	27.8%
	100	26.5%	30.8%	38.7%
	25C, 150M	19.4%	27.3%	breakdown

The difference in total corridor travel time between various models increased by up to 10.0% for a majority of cases with increase in corridor volumes (figure A.7). A difference of more than 10.0% from baseline was computed for cases with high mainline volumes and high access densities as well as high driveway volumes (> 100 vphpd). The highest increase was observed for case C20-M24-FA at high mainline volume, where the travel time increased to 14.0% at 50 vphpd and to 21.3% for 100 vphpd.

From figure 6.6, the reduction in average speed was up to 5% for most of the cases, with cases at high mainline volumes and high driveway volumes experiencing reduction in speeds of more than 5.0% and up to 26.4% (C20-M24-FA at 1900 vph and 100 vphpd). In addition, for a few high driveway volume cases at medium and low mainline volumes with 16 and 24 midblock driveways also show a decrease of more than 5.0% in the average speed as shown in figure 6.6.

Following are the main conclusions at the corridor-level for all the cases with 20 corner driveways and a varying range of midblock driveways from 8 to 24.

- With an increase in midblock driveway density from 8 to 16, across all driveway volumes the average delay increased in the range of 1.7% to 8.0% with larger difference in delays at high mainline volume. An increase in midblock density from 16 to 24 resulted in the same pattern of average delay increase but with higher differences ranging from 5.3% to about 10.0% (figure 6.5).
- For a given driveway volume, across all mainline volumes the difference in average delay between 8 and 16 midblock driveways was computed at approximately 0.6%, and the difference in delay between 16 and 24 midblock driveways was computed to be approximately 2.0% (figure 6.5).
- With low mainline volume, adding 20 corner driveways and incrementally adding midblock driveways from 8 to 24 increased the delay from 5.4% (from table 6.4) to 11.5% when driveway volumes were increased up to 150 vphpd. Similar increases in driveway volume and midblock densities increased the delays up to 21.2% (compared to 11.4% with corner driveways only, C20-FA) with medium mainline volume, and up to 25.5% (compared to 15.5% with C20-FA) with high mainline volume (table 6.6).
- Reduction in average speeds of more than 10.0% occurred for all high mainline volume cases especially at high driveway densities (figure 6.6).

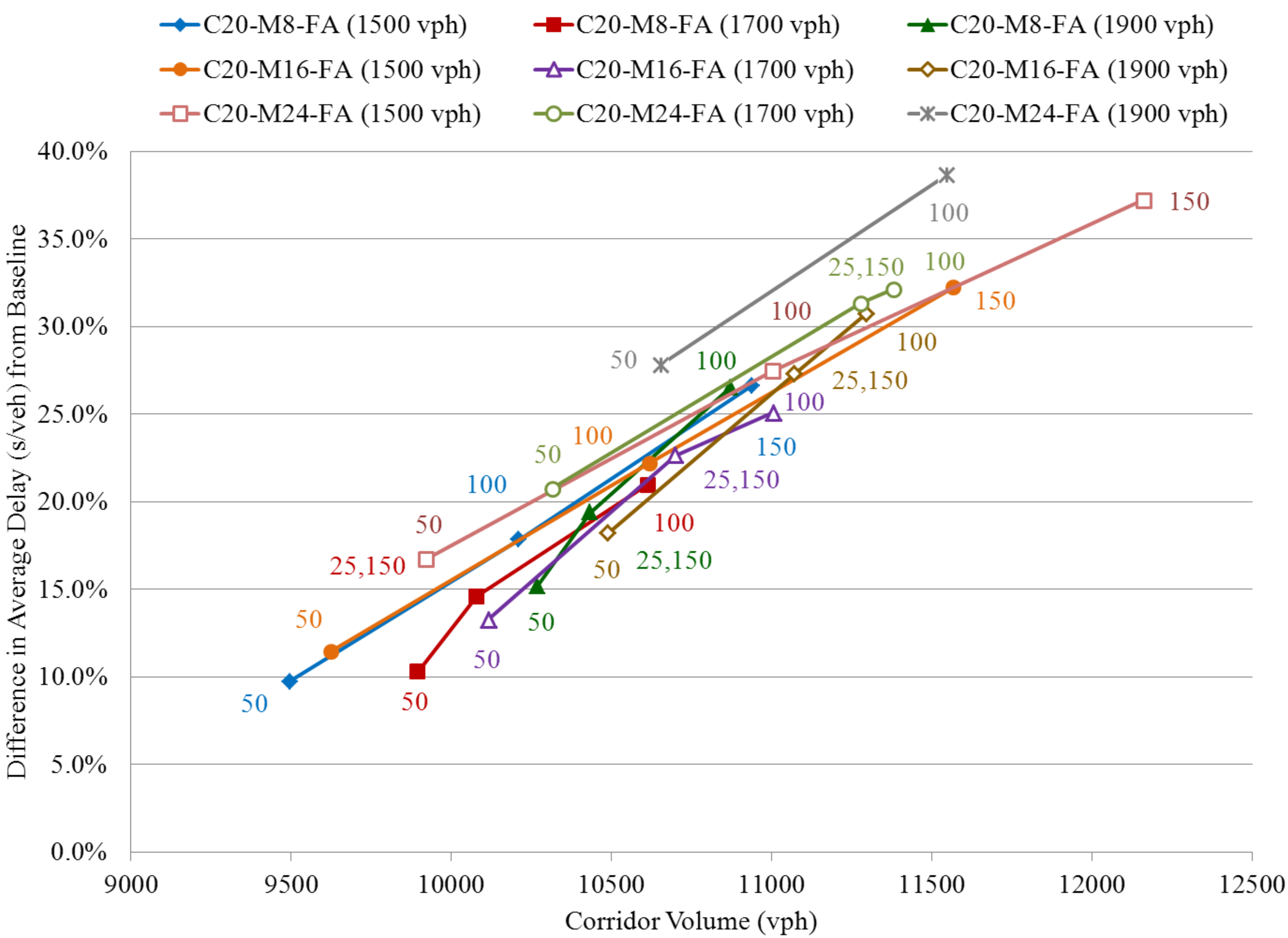

Figure 6.5 Corridor-wide Difference in Average Delay for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

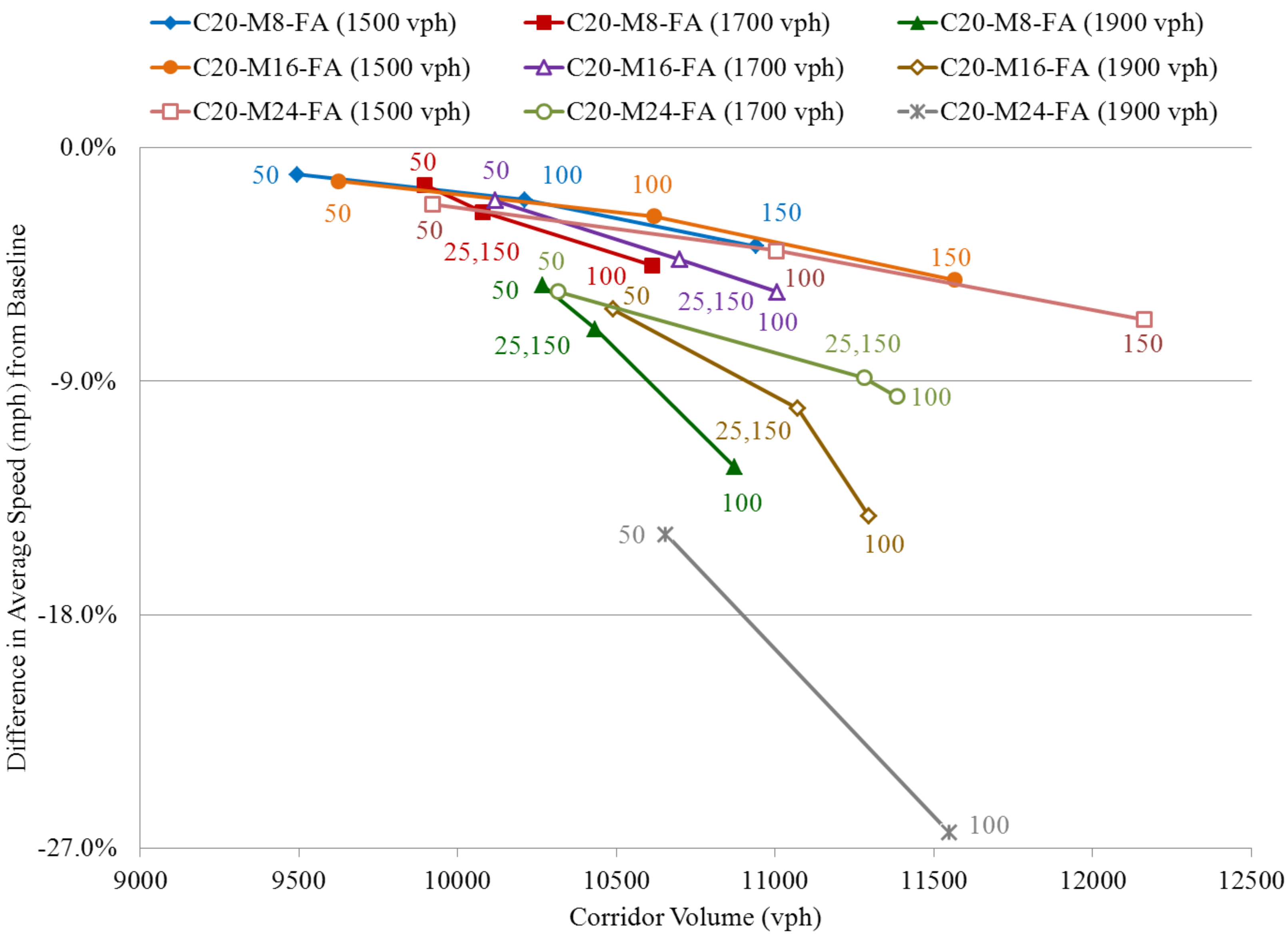

Figure 6.6 Corridor-wide Difference in Average Speed for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

6.2.4 Corridor-wide Evaluation of Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

Figures 6.7 and 6.8 show the corridor-wide MOEs for cases with 20 driveways at corners (C) and 8 to 24 midblock (M) driveways, all right-in/out (RR) only. Table 6.7 provides corridor-wide difference in average delay per vehicle which can be compared horizontally with increase in midblock driveway density, and vertically with varying mainline volume and/or driveway volume. Under all mainline volume and driveway density cases, the difference in average delays between 100 and 150 vphpd is slightly larger (10.1%) than that between 50 and 100 vphpd (9.4%). Increase in average delay of more than 40.0% is observed for high mainline volume at 150 vphpd with 24 midblock driveways. The reduction in average speed of 8.0% or more is noted (figure 6.8) for all the cases whose delays increased by more than 30.0%, with the highest reduction in speed occurred in case C20-M24 at high mainline and driveway volume (150 vphpd).

Table 6.7 Corridor-wide Difference in Average Delay for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

Mainline Volume (vph)	Driveway Volume (vphpd)	Case		
		C20-M8-RR	C20-M16-RR	C20-M24-RR
1500	50	9.1%	11.8%	15.7%
	100	17.5%	21.1%	26.6%
	150	27.1%	30.5%	35.4%
1700	50	9.0%	11.5%	18.1%
	100	16.5%	20.8%	28.5%
	150	26.6%	31.5%	37.6%
1900	50	8.0%	12.9%	22.4%
	100	17.1%	22.9%	32.4%
	150	29.7%	34.5%	41.6%

Difference from baseline in total travel time indicated an overall increasing trend with increase in driveway volumes as well as mainline volume (figure A.10). With low to medium mainline volumes and low driveway volumes (50 vphpd), the increase in travel times was <2.0% with 8 and 16 midblock driveways. Also at high mainline volume and with low midblock access density (C20-M8), the increase in travel time with 50 vphpd was <2.0%. Across all cases except C20-M24 at high volume, the difference in travel time from baseline (no driveways) was <8.0% for up to 100 vphpd, while differences for a given case with varying driveway volumes were up to 5.0%. More than 10.0% increase was recorded for all high mainline volume cases and also for medium mainline volume case at high midblock density at 150 vphpd. For C20-M24 at high mainline volume, the increase even at low (50 vphpd) driveway volume was close to 10.0%, and increasing further by 7.0% at 150 vphpd.

The following main conclusions are drawn for this set of theoretical models.

- With an increase in midblock driveway density from 8 to 16, across all driveway volumes the delays increased up to 4.0% with larger difference in delays at high mainline volume. An increase in midblock density from 16 to 24 resulted in a similar pattern of delay increase but with higher differences ranging from 3.9% to about 9.6% (figure 6.7).
- For a given driveway volume, across all mainline volumes the difference in delay between 8 and 16 midblock driveways was computed at approximately 4.1%, and the difference in delay between 16 and 24 midblock driveways was computed to be approximately 6.8% (figure 6.7).
- Compared to corresponding cases with full-access driveways (table 6.6), across all variables the right-in/out delays were only approximately 0.8% lower with a reduction

ranging from 0.3% to 12.0%. The pattern of differences between full-access and right-in/out driveway delays suggests that mainline volume has a higher impact in combination with high driveway volume on the total delay in the corridor.

- Compared to cases with only corner right-in/out driveways, adding midblock right-in/out driveways resulted in an increase in delays ranging from 8.3% to 11.2% with higher delays with increasing mainline as well as driveway volumes (table 6.7).

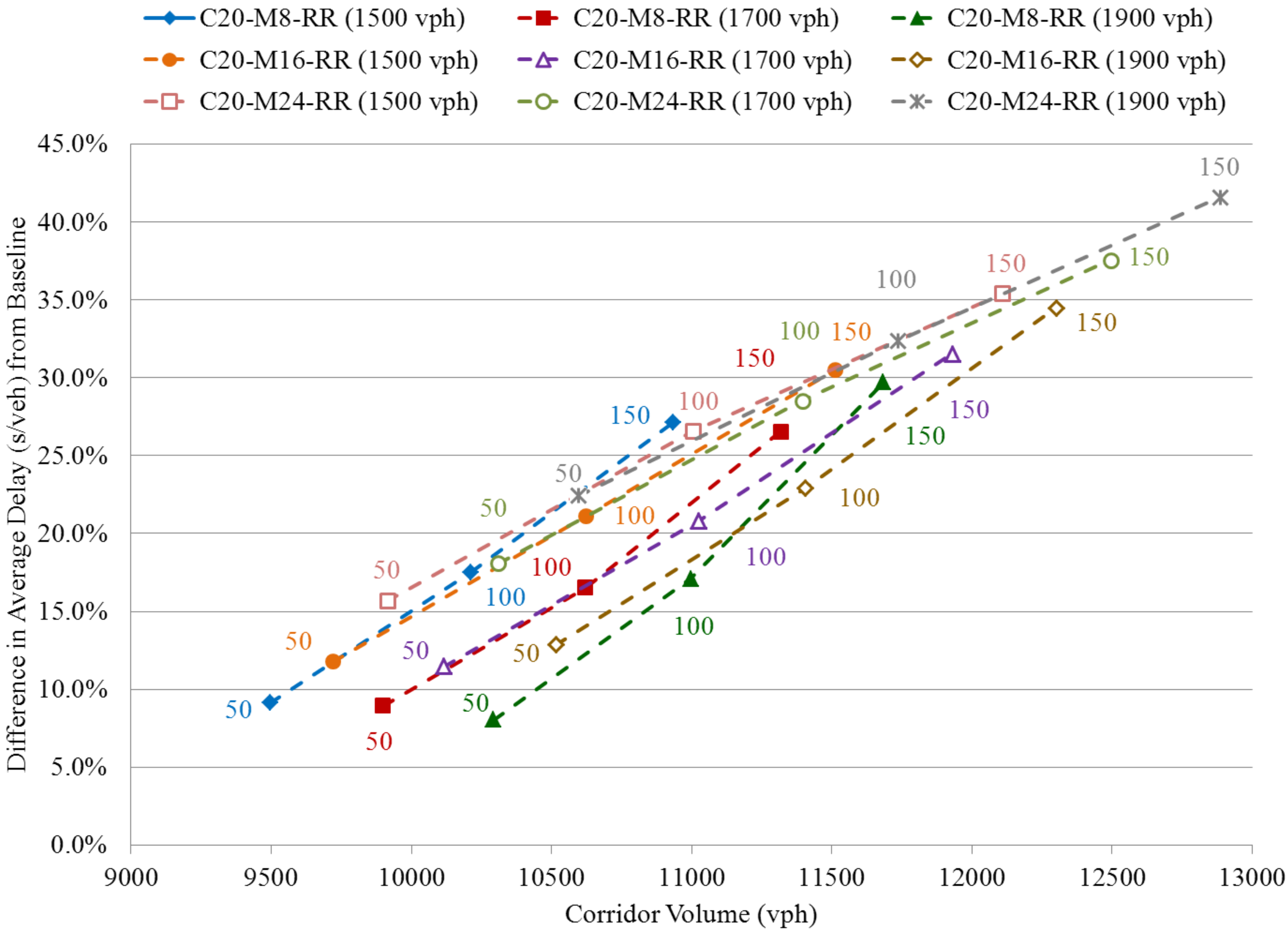

Figure 6.7 Corridor-wide Difference in Average Delay for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

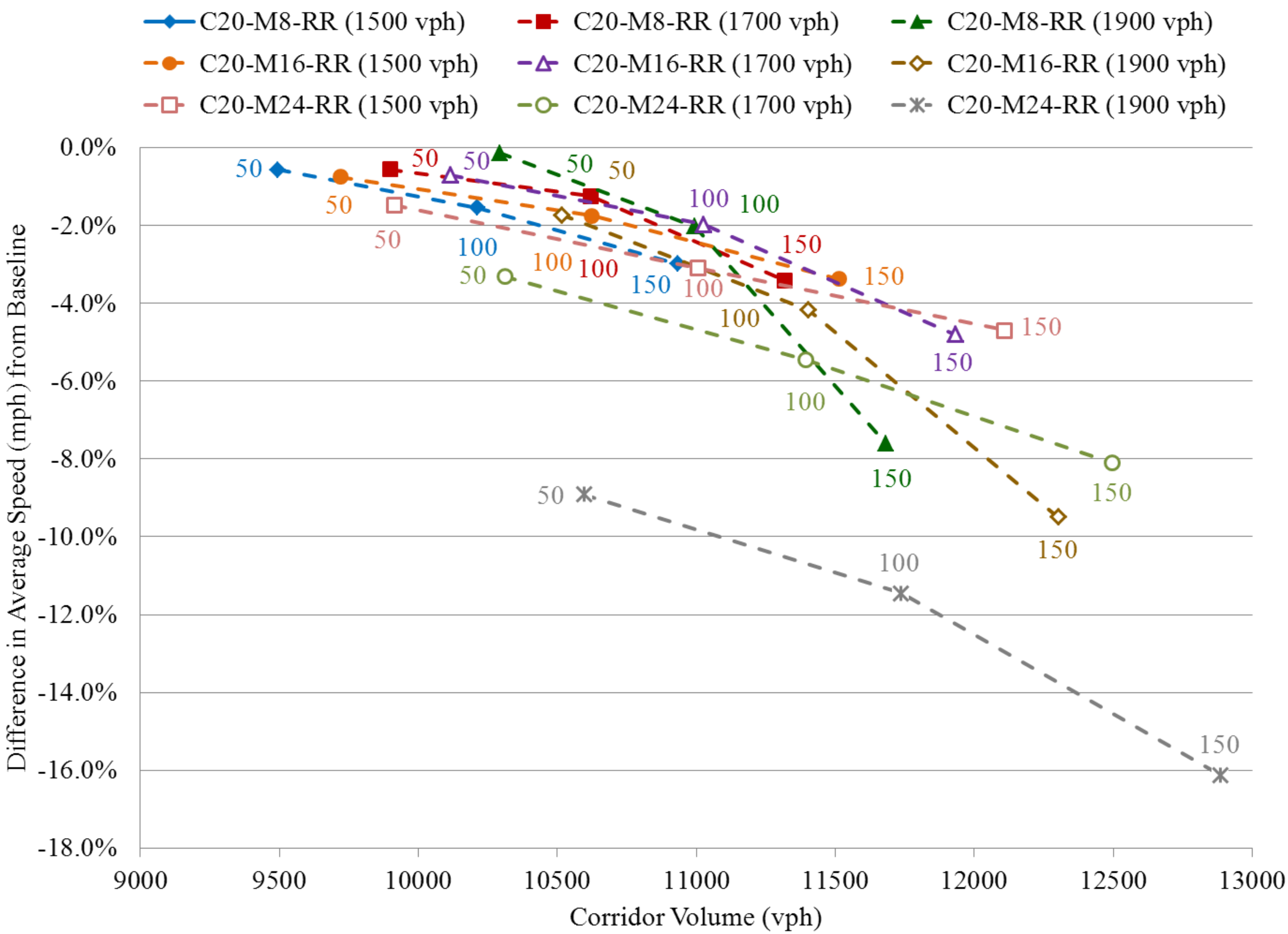

Figure 6.8 Corridor-wide Difference in Average Speed for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

6.2.5 Corridor-wide Evaluation of Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

In figures 6.9 and 6.10, differences in average delay per vehicle and average speed are shown for cases where all 20 corner (C) driveways were modeled as right-in/out (RR) and full-access (FA) midblock (M) driveways were incrementally added from 8 to 24 per mile.

In addition to figure 6.9, the average delays are also provided in table 6.8 which shows differences in delays from baseline as well as allows for comparison of cases within the modeled combinations of driveway density, mainline volume, and driveway volumes. Under all mainline volume and driveway density cases, the difference in average delays between 100 and 150 vphpd was slightly higher (10%) than that between 50 and 100 vphpd (9.4%).

Table 6.8 Corridor-wide Difference in Average Delay for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

Mainline Volume (vph)	Driveway Volume (vphpd)	Case		
		C20/RR-M8/FA	C20/RR-M16/FA	C20/RR-M24/FA
1500	50	9.4%	12.4%	16.4%
	100	17.8%	21.8%	27.0%
	150	25.9%	31.6%	36.2%
1700	50	8.8%	12.1%	19.1%
	100	17.2%	21.6%	29.5%
	150	26.1%	32.1%	39.2%
1900	50	9.7%	13.4%	24.6%
	100	17.9%	23.1%	34.8%
	150	29.7%	35.7%	breakdown

The differences in average speed in figure 6.10 indicate a decrease of more than 5.0% across all cases with high access density and driveway volume, and also for medium mainline volume with 16 midblock driveways. Increase in travel times in the range of 2.0% to 3.0% was noted (figure A.13) when the driveway volume was increased from 50 to 100 vphpd for a given driveway density and mainline volume combination, except at C20/RR-M24/FA when the travel time increased by about 4.0%. When the driveway volume increased from 100 to 150 vphpd, the travel times increased from 4.0% to 5.0% for all cases except at high mainline volume cases where the travel time increased by approximately 8.0%.

Key results for the set of cases with mixed driveway access conditions are as follows.

- With an increase in midblock driveway density from 8 to 16, the average delays increased in the range of 3.0% to 6.0% across all driveway volumes. With an increase in midblock driveway density from 16 to 24, across all driveway volumes the delays increased in the range of 4.0% to 12.0% (figure 6.9, table 6.8).
- Compared to corresponding cases with all full-access driveways (table 6.6), across all variables the delays for mixed driveways were only approximately 0.1% lower with a reduction ranging from 0.3% to 11.5%. The pattern of differences between full-access and mixed driveway delays suggests higher impact of driveway volume on the average delay in the corridor.
- Compared to corresponding cases with all right-in/outs driveways (table 6.7), across all variables the average delays for mixed driveways were approximately 0.7% higher with a reduction ranging from 0.0% to 2.5%.

The corridor-wide evaluation of theoretical models suggests that as expected, high mainline volumes combined with high driveway volumes as well as high access densities have the largest impact on travel times, delays, and average speeds of the network. The operational impacts in terms of actual quantitative differences between various conditions were determined from the system-wide outcomes of these models. In terms of the significance of differences between a pair of scenarios, it is highly dependent on the initial conditions in the corridor. For example, a 2.0% increase in delay due to additional driveway(s) in a corridor experiencing low overall (or per vehicle) delay may not be significant, but if a highway or a part thereof is already approaching congested conditions during the peak hour, additional driveways or change in access for existing driveways may become operationally significant even with low driveway volumes. The quantification of traffic operations based on varying volumes, densities, and access types will be informative to the traffic analysts in determining the corridor-wide impacts at least in a general sense. More specific impacts at the signalized intersections and driveways are presented in the next section.

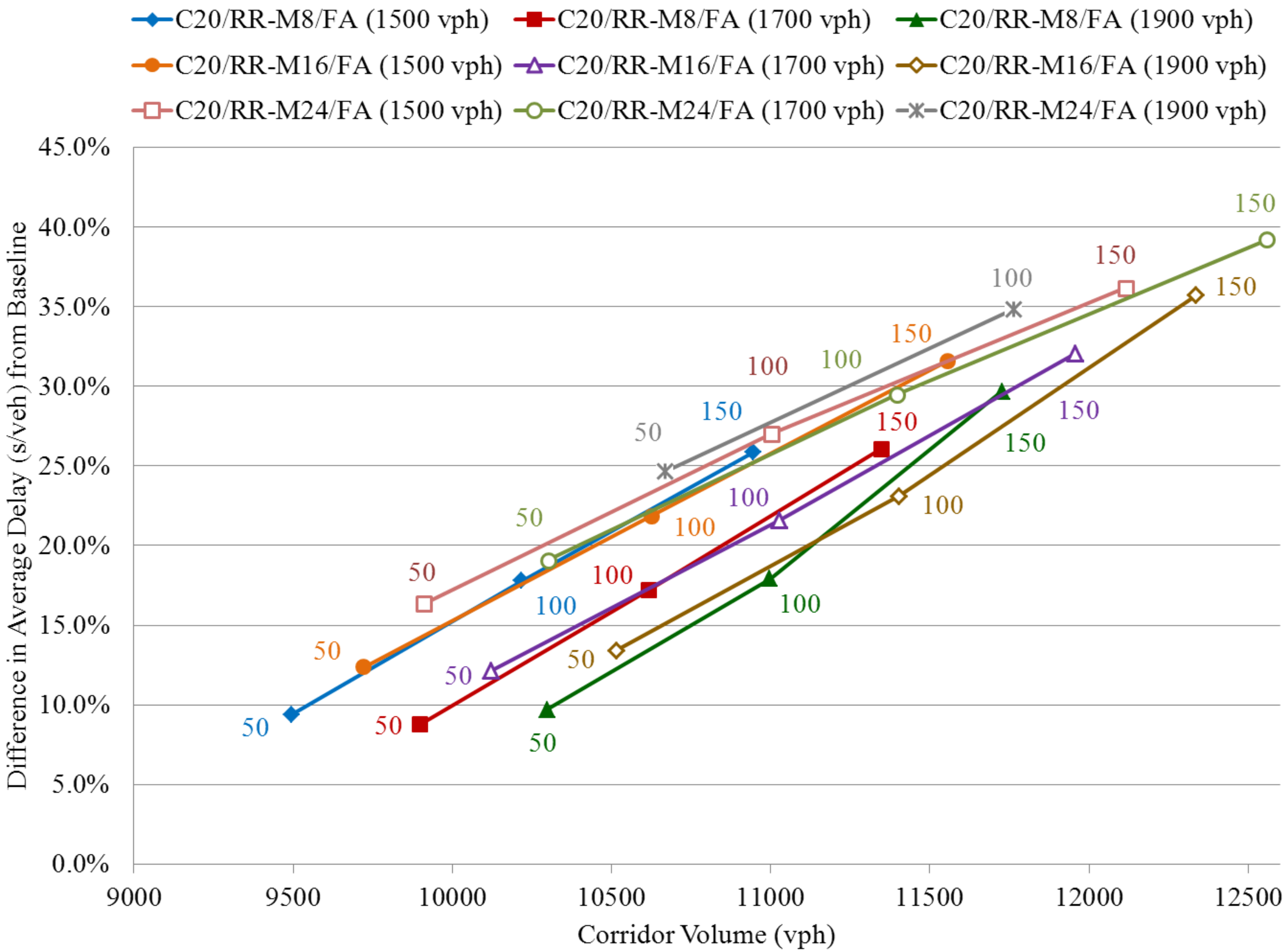

Figure 6.9 Corridor-wide Difference in Average Delay for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

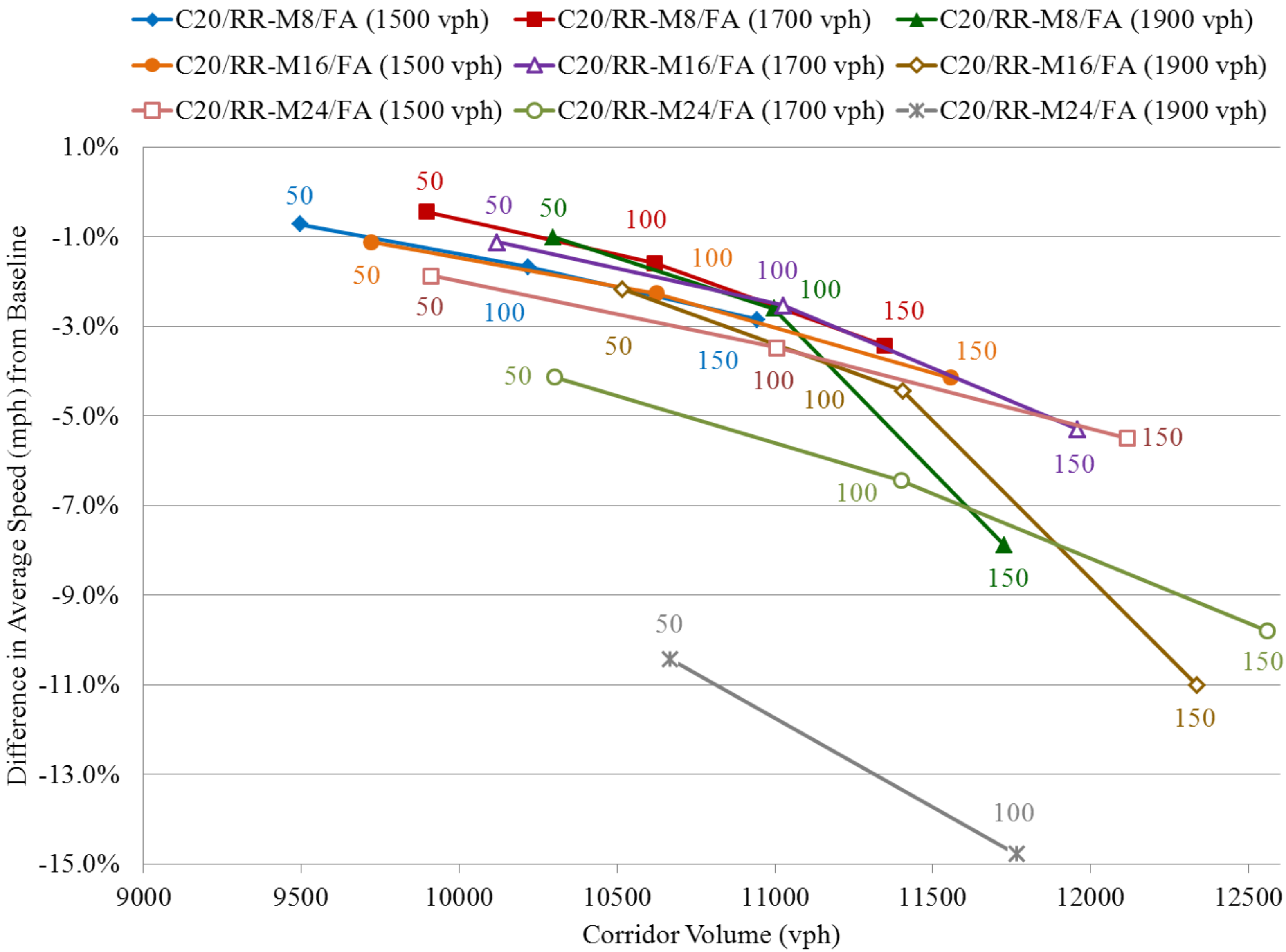

Figure 6.10 Corridor-wide Difference in Average Speed for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.3 Evaluation of Signalized Intersections

The MOEs for signalized intersections were computed using the ‘node evaluation’ feature in VISSIM. Intersection nodes were defined for each signalized intersection in all theoretical models to aggregate hourly data on overall intersection delay (s/veh), delay by movement (left/ through/right), delay by approach (EB/WB/NB/SB), and queue lengths by movement and movement group (ft). Overall intersection delays are presented in this section for all five signalized intersections for each case. To determine the significance of change in intersection delay for a given set of cases, the level of service (LOS) criteria for signalized intersections from the Highway Capacity Manual (HCM) are presented in table 6.9. When comparing intersection delays, it is important to note that each signalized intersection was optimized to reduce the mainline delays (EB and WB) in all the baseline cases to the extent that side-street (NB and SB) delays did not go beyond LOS D. Then, coordination offsets were optimized for mainline flows using Synchro and input to the theoretical models. Therefore, direct comparison between low, medium, and high mainline volume cases is compounded by differences in traffic splits (by direction as well as by movement), cycle lengths, phase splits, and coordination between intersections. In terms of the total approach volume on the mainline at each intersection, the driveway traffic was distributed in a way that minimized the differences in the mainline approach volumes for comparable set of cases. In addition to the average delay, 95^{th} percentile queue lengths were also checked (especially for EB/WB) after each model run to determine the extent of queues in extreme cases.

Table 6.9 Level of Service Criteria for Signalized Intersections[1]

Level of Service	Average Control Delay (s/veh)	General Description
A	≤ 10	Free flow
B	> 10 – 20	Stable flow (slight delays)
C	> 20 – 35	Stable flow (acceptable delays)
D	> 35 – 55	Approaching unstable flow (tolerable delay, occasionally wait through more than one signal cycle before proceeding)
E	> 55 – 80	Unstable flow (intolerable delay)
F	> 80	Forced flow (jammed)

[1]Source: Highway Capacity Manual *(65)*

Figures 6.11 to 6.17 show all the theoretical models and corresponding driveway locations and intersection numbers. With each figure, a companion table is shown (tables 6.10 to 6.15) that provides intersection delays (s/veh) for each case shown in the corresponding figure. The intersection delays are color-coded for an easier comparison between changes in LOS. LOS B is shown in **blue**, and LOS C is shown in **red**. None of the intersections in any case operated at a LOS A, or LOS D and worse. Intersection delays for all three baseline cases are also shown in table 6.10. Cells with blank values were combinations that were either not modeled or experienced a breakdown as described earlier.

For the baseline cases, all intersections operate at LOS C with high mainline volume, and either LOS B or C for low and medium mainline volume. In all the cases, intersections 2 and 4 have lower overall delay because their NB and SB approach volume is 400 vph per direction compared to intersections 1, 3, and 5 where NB and SB approach volume was set at 700 vph per direction. Across all driveway locations, densities, driveway volumes, and mainline volumes, the intersection LOS does not change indicating minor changes in overall delays and within an acceptable range for stable flow (table 6.9). Across all cases for high mainline volume, all intersections operate at LOS C. For all low and medium mainline volume cases, intersections 1, 3, and 5 operate at LOS C, and intersections 2 and 4 operate at LOS B. Again, note that while case-to-case variation in overall intersection delay may not be significant, variation in delays by approach (and corresponding queue lengths) may be significant to have an impact on driveway traffic. These effects are measured (albeit indirectly) for driveway-specific delays as described in the next section.

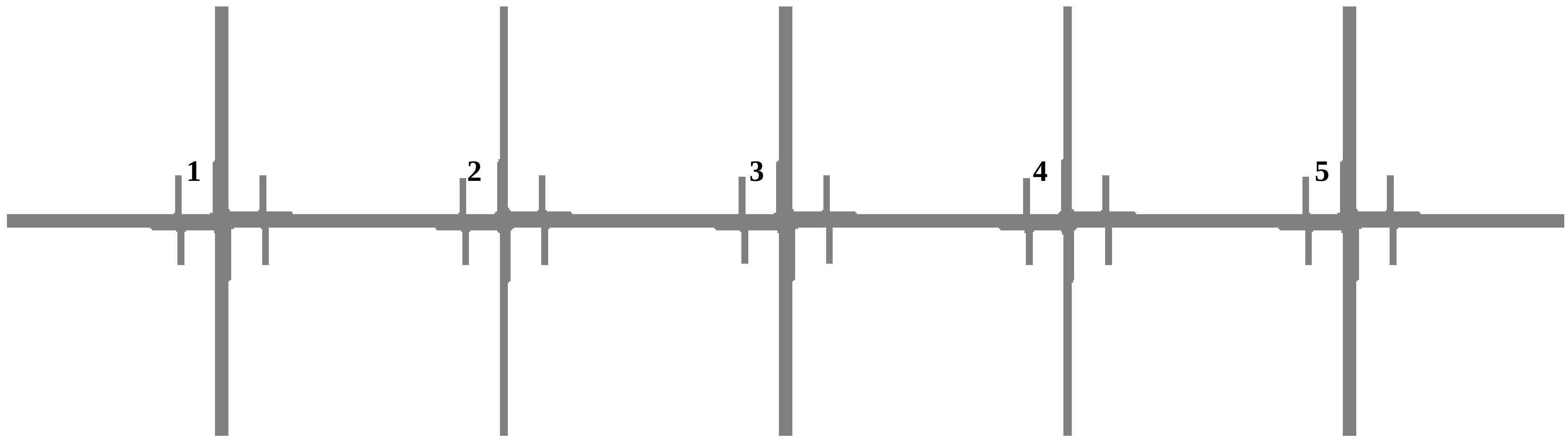

Figure 6.11 Cases C20-FA and C20-RR

Table 6.10 Intersection Delay for Cases C20-FA and C20-RR (For interpretation of the references to color in this and all other tables, the reader is referred to the electronic version of this dissertation).

		Intersection Delay (s/veh)														
Case	**Int #**	**1**			**2**			**3**			**4**			**5**		
	Dwy Vol	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Baseline	0	21.9	27.0	31.0	19.1	15.1	25.0	22.0	32.4	20.7	19.1	14.7	24.6	21.9	26.4	30.1
C20-FA	25		27.1	31.2		15.4	23.3		32.6	21.9		15.6	23.8		26.6	30.9
	50	22.0	26.6	31.0	18.8	15.6	24.3	22.1	31.9	20.6	18.9	15.4	23.8	21.9	26.2	30.1
	100	21.9	26.4	30.4	18.5	15.9	25.2	22.1	31.2	21.6	18.8	16.0	25.1	21.8	26.0	29.7
	150	22.2			18.8			22.2			19.1			22.1		
C20-RR	50	22.1	26.9	31.2	18.9	15.1	24.4	22.2	31.9	20.7	19.2	15.4	24.1	21.7	26.5	30.2
	100	22.0	26.4	30.5	19.0	15.4	24.7	22.3	31.6	21.3	19.0	15.5	24.5	21.8	26.1	30.0
	150	22.4	27.0	31.7	19.3	16.2	25.5	22.5	32.4	22.4	19.2	16.1	25.7	22.0	26.6	30.9

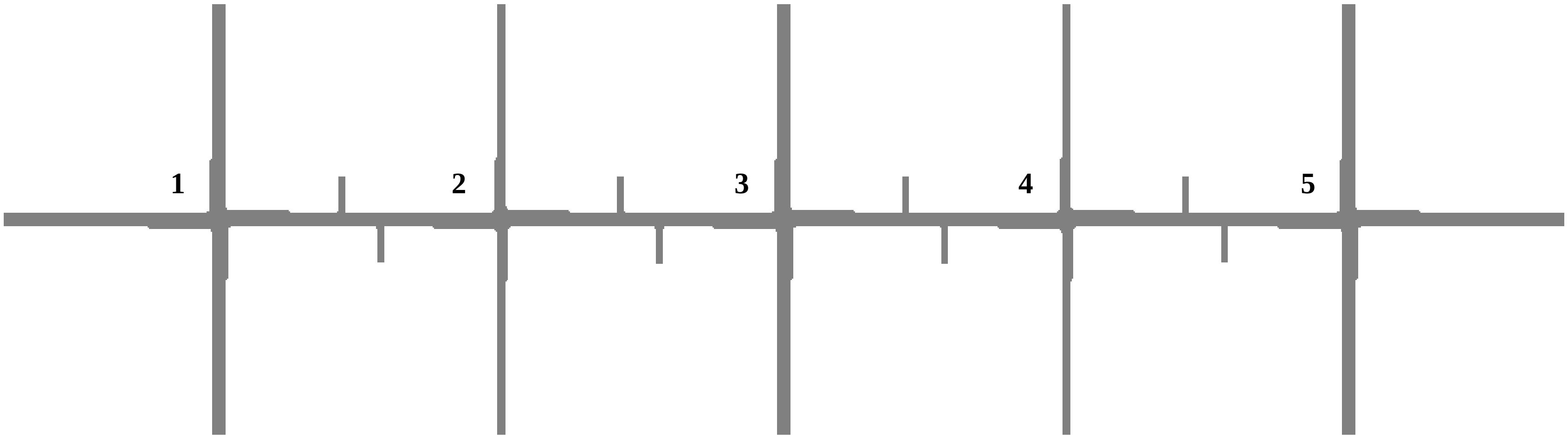

Figure 6.12 Cases M8-FA and M8-RR

Table 6.11 Intersection Delay for Cases M8-FA and M8-RR

		Intersection Delay (s/veh)														
Case	**Int #**	**1**			**2**			**3**			**4**			**5**		
	Dwy Vol	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
M8-FA	50			**31.5**			**24.9**			**21.7**			**25.0**			**30.8**
	100	**21.7**	**26.6**	**31.0**	**18.7**	**15.3**	**24.0**	**22.1**	**31.7**	**21.4**	**18.9**	**15.5**	**24.6**	**21.7**	**26.2**	**30.1**
	200	**21.8**	**26.4**	**31.9**	**18.5**	**15.5**	**26.0**	**21.6**	**31.4**	**21.1**	**18.6**	**15.7**	**24.7**	**21.6**	**26.0**	**30.4**
M8-RR	100	**21.8**	**26.7**	**31.2**	**18.7**	**15.0**	**24.4**	**21.9**	**31.8**	**21.3**	**18.9**	**15.4**	**24.6**	**21.8**	**26.2**	**30.4**
	200	**21.8**	**26.6**	**31.6**	**18.3**	**15.9**	**25.6**	**21.6**	**31.3**	**22.2**	**18.5**	**16.2**	**25.5**	**21.6**	**25.9**	**30.8**

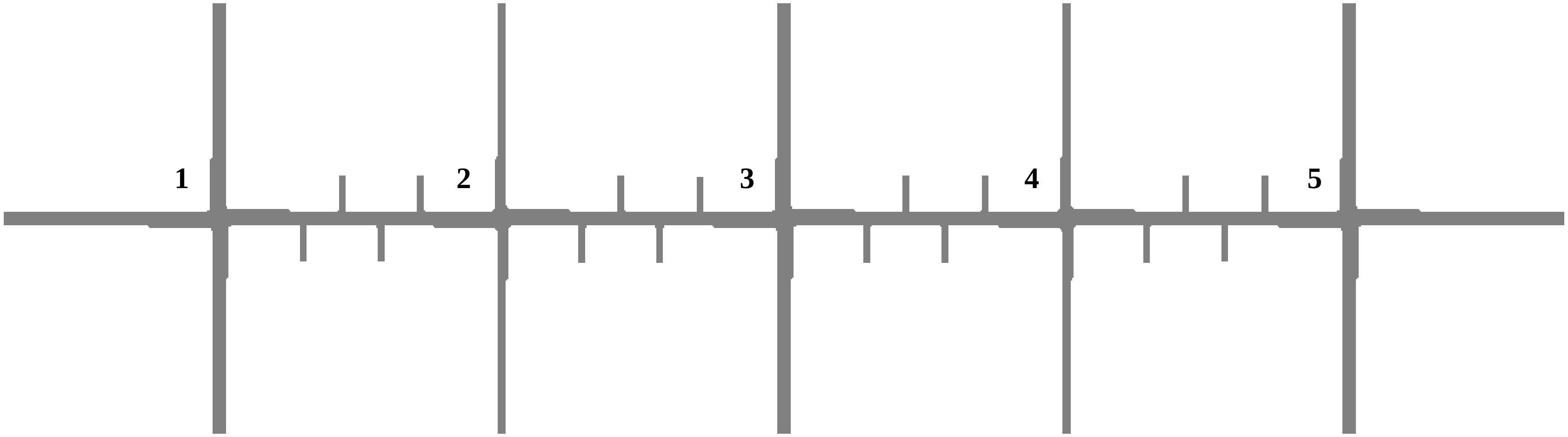

Figure 6.13 Cases M16-FA and M16-RR

Table 6.12 Intersection Delay for Cases M16-FA and M16-RR

		Intersection Delay (s/veh)														
Case	**Int #**	**1**			**2**			**3**			**4**			**5**		
	Dwy Vol	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
M16-FA	100	**21.7**	**26.2**	**31.3**	**18.5**	**15.9**	**24.6**	**21.6**	**31.0**	**21.2**	**18.8**	**15.6**	**24.7**	**21.7**	**25.9**	**30.1**
	200	**21.4**	**25.7**	**31.4**	**18.3**	**16.1**	**25.3**	**21.0**	**30.1**	**22.9**	**18.3**	**16.5**	**25.5**	**21.4**	**25.5**	**30.8**
M16-RR	100	**21.6**	**26.6**	**31.5**	**18.2**	**15.1**	**24.7**	**21.7**	**31.4**	**21.4**	**18.5**	**15.7**	**25.0**	**21.4**	**26.2**	**30.8**
	200	**21.3**	**25.9**	**31.8**	**17.6**	**16.3**	**26.1**	**20.9**	**30.3**	**23.2**	**17.8**	**17.4**	**26.3**	**21.1**	**25.6**	**30.8**

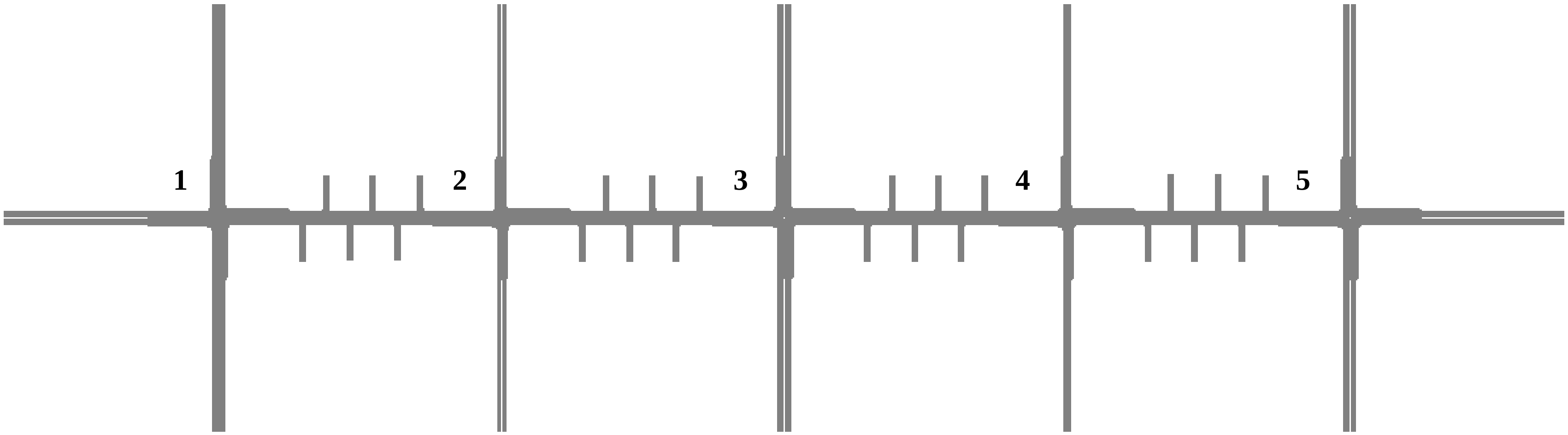

Figure 6.14 Cases M24-FA and M24-RR

Table 6.13 Intersection Delay for Cases M24-FA and M24-RR

		Intersection Delay (s/veh)														
Case	**Int #**	**1**			**2**			**3**			**4**			**5**		
	Dwy Vol	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
M24-FA	50			**33.8**			**17.4**			**25.9**			**28.3**			**32.0**
	100	**21.8**	**26.7**			**18.9**	**28.5**	**21.8**	**31.5**		**19.1**	**18.2**		**21.6**	**26.1**	
	150	**21.7**			**18.7**			**21.6**			**18.8**			**21.7**		
	200	**21.5**			**18.8**			**21.1**			**18.4**			**21.5**		
M24-RR	100	**21.4**	**26.8**	**33.0**	**18.3**	**17.4**	**28.3**	**21.3**	**31.6**	**26.5**	**18.9**	**18.2**	**28.7**	**21.5**	**26.3**	**32.3**
	200	**21.1**	**26.3**	**33.4**	**18.0**	**19.7**	**30.5**	**20.8**	**31.2**	**28.4**	**18.2**	**19.9**	**31.8**	**21.3**	**26.2**	**33.3**

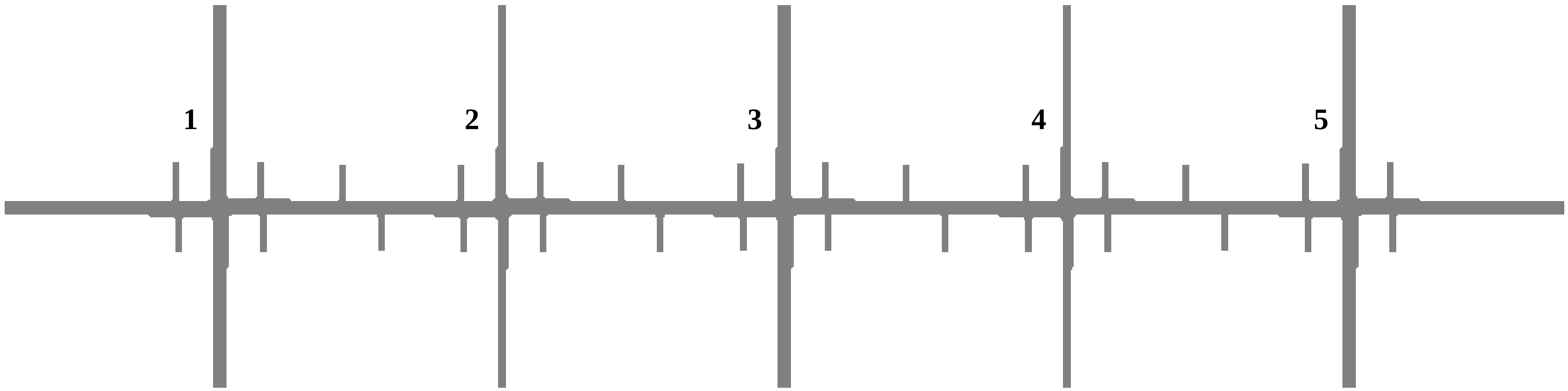

Figure 6.15 Cases C20-M8-FA, C20-M8-RR, and C20/RR-M8/FA

Table 6.14 Intersection Delay for Cases C20-M8-FA, C20-M8-RR, and C20/RR-M8/FA

		Intersection Delay (s/veh)														
Case	**Int #**	**1**			**2**			**3**			**4**			**5**		
	Dwy Vol	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
C20-M8-FA	50	21.9	26.6	30.9	18.9	15.3	24.7	22.0	31.5	21.2	18.9	15.3	24.1	21.9	26.3	30.0
	100	21.9	26.5	30.3	18.4	15.9	23.8	22.1	30.5	21.3	18.7	16.2	24.4	21.6	25.9	30.0
	150	22.1			19.1			21.9			18.8			21.9		
	25C,150M		26.4	31.8		16.3	25.7		31.6	22.6		16.0	25.1		26.0	30.7
C20-M8-RR	50	22.0	26.6	31.0	18.8	15.1	24.2	22.1	32.1	20.3	19.0	15.2	24.6	21.7	26.6	30.3
	100	22.0	26.3	31.3	18.9	15.7	24.3	22.1	31.4	21.2	18.9	15.8	24.9	21.7	26.3	30.5
	150	22.4	27.3	32.4	19.2	16.2	26.1	22.4	31.5	23.5	19.0	16.8	26.8	21.8	26.7	32.1
C20/RR-M8/FA	50	22.0	26.6	31.3	18.8	15.0	23.9	22.2	31.7	20.8	19.0	15.1	24.4	21.7	26.4	30.2
	100	21.9	26.4	31.2	18.8	15.4	24.1	22.1	31.4	21.0	19.0	15.8	24.8	21.8	26.2	30.5
	150	22.1	26.7	32.0	19.0	16.1	25.4	22.1	31.2	23.3	18.9	16.9	25.9	21.7	26.2	31.5

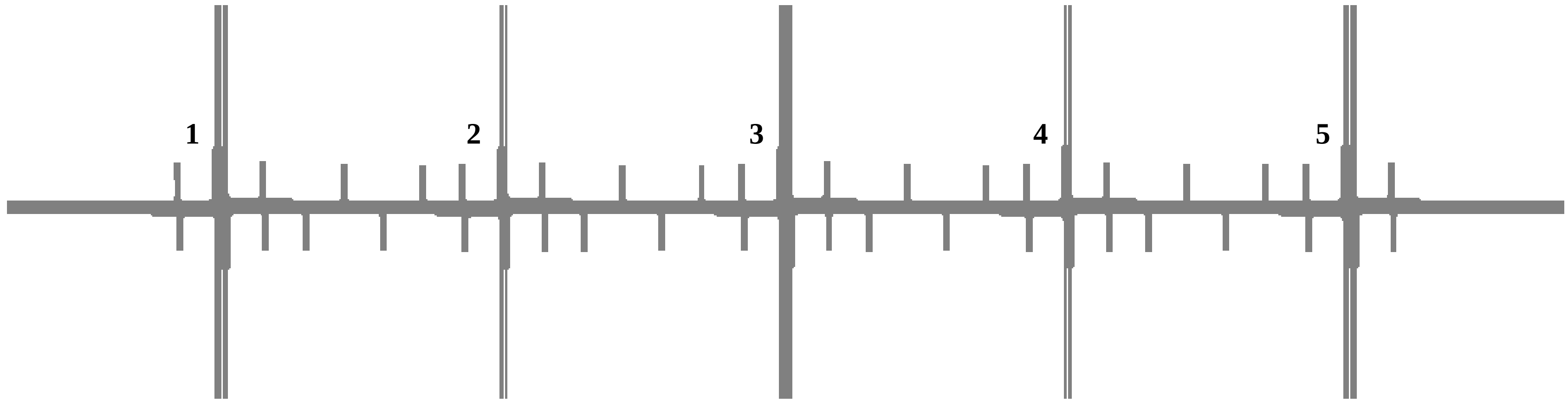

Figure 6.16 Cases C20-M16-FA, C20-M16-RR, and C20/RR-M16/FA

Table 6.15 Intersection Delay for Cases C20-M16-FA, C20-M16-RR, and C20/RR-M16/FA

		Intersection Delay (s/veh)														
Case	**Int #**	**1**			**2**			**3**			**4**			**5**		
	Dwy Vol	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
C20-M16-FA	50	**21.9**	**26.2**	**30.8**	**18.6**	**15.7**	**24.6**	**21.9**	**30.8**	**21.1**	**18.8**	**15.9**	**23.9**	**21.7**	**25.8**	**29.9**
	100	**21.7**	**26.1**	**30.8**	**18.4**	**16.2**	**24.3**	**21.8**	**30.2**	**22.6**	**18.5**	**16.7**	**24.4**	**21.7**	**25.6**	**30.2**
	150	**21.8**			**18.5**			**22.0**			**18.9**			**21.6**		
	25C,150M		**26.3**	**31.6**		**16.3**	**25.2**		**30.9**	**23.7**		**16.8**	**25.8**		**25.8**	**31.1**
C20-M16-RR	50	**21.8**	**26.5**	**31.1**	**18.6**	**15.3**	**24.7**	**21.9**	**31.6**	**21.6**	**18.8**	**15.4**	**24.5**	**21.5**	**26.1**	**30.8**
	100	**21.6**	**26.1**	**31.5**	**18.3**	**16.1**	**25.0**	**21.9**	**30.5**	**22.1**	**18.4**	**16.5**	**25.3**	**21.5**	**25.9**	**30.9**
	150	**22.0**	**26.8**	**32.2**	**18.6**	**17.4**	**26.9**	**21.6**	**31.2**	**24.5**	**18.6**	**17.3**	**27.5**	**21.6**	**26.0**	**31.5**
C20/RR-M16/FA	50	**21.9**	**26.5**	**31.0**	**18.6**	**15.4**	**24.6**	**22.1**	**31.5**	**21.8**	**18.9**	**15.3**	**24.7**	**21.5**	**26.2**	**30.1**
	100	**21.8**	**26.0**	**30.8**	**18.5**	**15.9**	**24.2**	**21.9**	**30.7**	**21.8**	**18.7**	**16.2**	**25.1**	**21.7**	**25.8**	**30.7**
	150	**22.0**	**26.4**	**31.9**	**19.0**	**16.6**	**26.1**	**21.9**	**30.9**	**24.2**	**18.9**	**16.9**	**27.3**	**21.6**	**26.0**	**31.4**

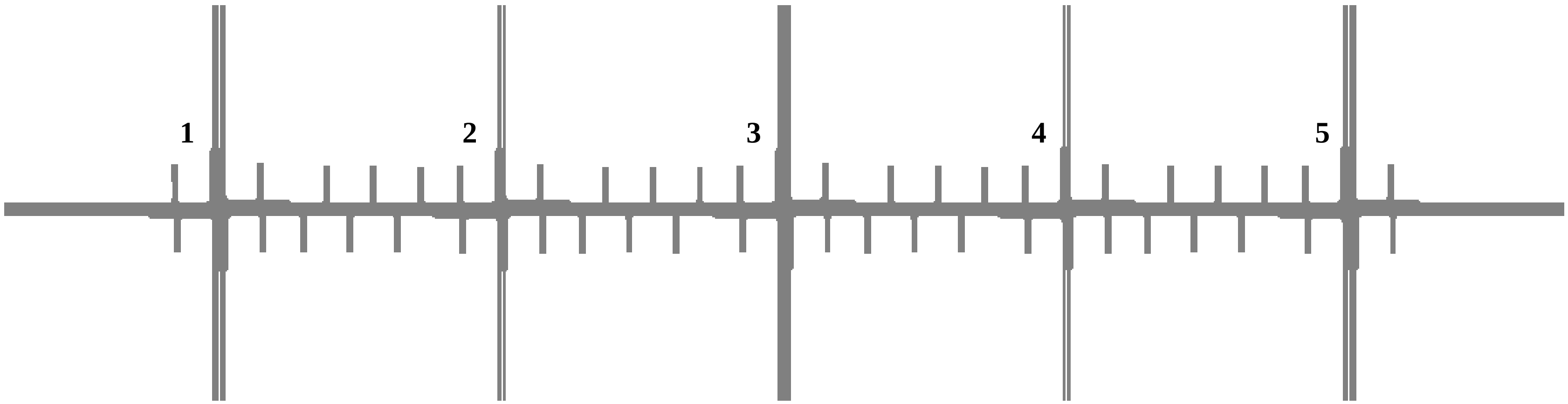

Figure 6.17 Cases C20-M24-FA, C20-M24-RR, and C20/RR-M24/FA

Table 6.16 Intersection Delay for Cases C20-M24-FA, C20-M24-RR, and C20/RR-M24/FA

		Intersection Delay (s/veh)														
Case	Int #	1			2			3			4			5		
	Dwy Vol	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
C20-M24-FA	50	21.8	26.9	32.5	19.0	17.7	27.0	21.9	31.7	25.0	19.2	18.0	27.6	21.7	26.5	32.0
	100	21.8	26.4	32.2	18.6	18.4	28.5	21.7	30.8	26.2	18.9	18.2	28.4	21.7	26.2	32.1
	150	22.0			19.2			22.0			19.0			21.7		
	25C,150M		26.6			18.6			31.7			19.3			26.0	
C20-M24-RR	50	21.8	27.0	32.9	18.7	17.4	27.5	21.9	31.8	25.2	19.2	17.3	29.1	21.6	26.7	32.3
	100	21.9	26.7	33.2	18.5	18.5	28.1	21.8	31.7	25.3	18.9	18.6	29.8	21.6	26.6	32.7
	150	22.0	26.9	33.3	18.5	19.5	29.8	22.0	31.3	27.7	18.7	19.9	31.5	21.7	26.4	32.8
C20/RR-M24/FA	50	21.9	27.0	32.9	18.9	17.4	28.4	22.0	31.7	24.6	19.3	18.1	28.6	21.7	26.4	32.5
	100	21.7	26.6	32.2	19.0	18.0	29.4	21.9	31.5	25.7	18.8	18.7	30.3	21.8	26.3	32.1
	150	22.0	26.5		18.9	19.0		22.1	31.8		19.1	20.0		21.7	26.1	

6.4 Evaluation of Driveways

The evaluation of driveway-related MOEs was based on the data collected for each permissible movement (inbound, outbound, and TWLTL-related) for every driveway for a given case, and then aggregated over the analysis hour for all driveways in the corridor. The following variables were measured: average delay (s/veh), average stop delay (s/veh), average number of stops, average queue length (ft), and maximum queue length (ft). Only the average delay (s/veh) is discussed in this chapter for consistency with other analyses at corridor and intersection levels. To establish the significance of differences between cases, LOS criteria for unsignalized intersections are used as shown in table 6.16.

Table 6.17 Level of Service Criteria for Unsignalized Intersections[1]

Level of Service	Average Control Delay (s/veh)
A	0 – 10
B	> 10 – 15
C	> 15 – 25
D	> 25 – 35
E	> 35 – 50
F	> 50

[1]Source: Highway Capacity Manual *(65)*

The driveway evaluation graphs are presented in figures 6.18 to 6.55, and are organized as follows.

- Figures 6.18 to 6.23 present the average delay (s/veh) for all driveway-related movements for all the theoretical cases modeled.

- Figures 6.24 to 6.29 present the average delay (s/veh) for all out-bound driveway movements for all the cases.
- Figures 6.30 to 6.33 present the average delay (s/veh) for all right-out driveway movements for all the cases.
- Figures 6.34 to 6.37 present the average delay (s/veh) for all left-out driveway movements for all applicable cases.
- Figures 6.38 to 6.41 present the average delay (s/veh) for all left-in driveway movements (from TWLTL) for all applicable cases.
- Figures 6.42 to 6.44 present the average delay (s/veh) for all driveway-related movements in TWLTL (where applicable) when the vehicles were waiting to merge onto the mainline.
- Figures 6.45 to 6.47 present the average delay (s/veh) for all TWLTL-related driveway movements (left-in and merging) for all applicable cases.
- Figures 6.48 to 6.51 present the average delay (s/veh) for all corner driveways located on the approach side of signalized intersections.
- Figures 6.52 to 6.55 present the average delay (s/veh) for all corner driveways located on the departure side of signalized intersections.

In addition to the data from the simulation models, HCM based unsignalized intersection average delay thresholds for LOS (table 6.16) are also plotted on each graph for ease of comparison between cases. Similar to corridor-wide evaluation, all full-access cases are plotted with continuous lines, and all right-in/out cases are plotted with dashed lines. For the evaluation of driveway-related delays, the data are plotted against driveway volume modeled for each case instead of total simulated volume used for corridor-wide evaluation. The actual volume per driveway produced in each case was also computed and compared against the input volume. The difference between the simulated driveway volumes and the actual input volumes was found to be <1.0% across all cases as described in chapter 5. Also, using the driveway input volume instead of the actual simulated volume provides for an easier comparison of results among cases. Note that the driveway volumes on the abscissae represent the total volume for all permissible in-bound and out-bound movements for a given case. The main conclusions for each set of delays reported are presented separately.

6.4.1 Comparison of Average Delays for All Driveway Movements

In figures 6.18 to 6.23, the overall average delay (s/veh) for all driveway-related movements is presented for all the theoretical cases modeled. Following are the main outcomes from this set of analysis.

- For case C20-FA (20 corner full-access driveways), with medium and high mainline volume and across all driveway volumes, the average driveway delay was at LOS D or worse (figure 6.18). For corresponding cases with right-in/out (C20-RR) driveways, the LOS was C or better across all driveway and mainline volumes. Note that full-access corner driveways on the approach side did not have the left-in movement permitted in any model.
- For all the cases modeled with only midblock full-access driveways (figure 6.19), the LOS was B or better except at M8-FA at 200 vphpd where the delay increased to approximately16 s/veh (LOS C).

- For all the cases modeled with midblock right-in/out driveways, the LOS was A with average delay <1.5 s/veh across all combinations of volumes and densities (figure 6.20).
- For cases with both corner and midblock full-access driveways, at high mainline volume the LOS was F across all driveway volumes and densities (figure 6.21). At medium mainline volumes, the LOS was C or worse with increasing driveway volumes. Note that the disconnected points in a given series in figure 6.21 are for cases with different volumes for corner (25 vphpd) and midblock (150 vphpd) driveways. At low mainline volume, the LOS for all cases was at A.
- For cases with both corner and midblock right-in/out driveways, the LOS was B or better across all cases except C20-M24 at high mainline volume with 150 vphpd at LOS C (figure 6.22).
- For cases with corner right-in/out and midblock full-access driveways, at low and medium mainline volumes the LOS was A across all driveway volumes and densities (figure 6.23). At high mainline volume up to 100 vphpd and 16 midblock driveways, the LOS was B. The LOS was at C with high midblock access density (24 driveways per mile) across all driveway volumes modeled.
- From the overall driveway delay across all models, the corner full-access driveways always operated at LOS F at medium and high mainline volumes. Note that the delays for midblock-only driveway cases were not excessive (LOS C or better) even at high driveway volumes, however the upper limit on the driveway density modeled was primarily a factor of VISSIM’s ability to model closely-spaced driveways by providing space for storage in the TWLTL rather than a driveways maximum ability to handle traffic volume at acceptable levels of service.

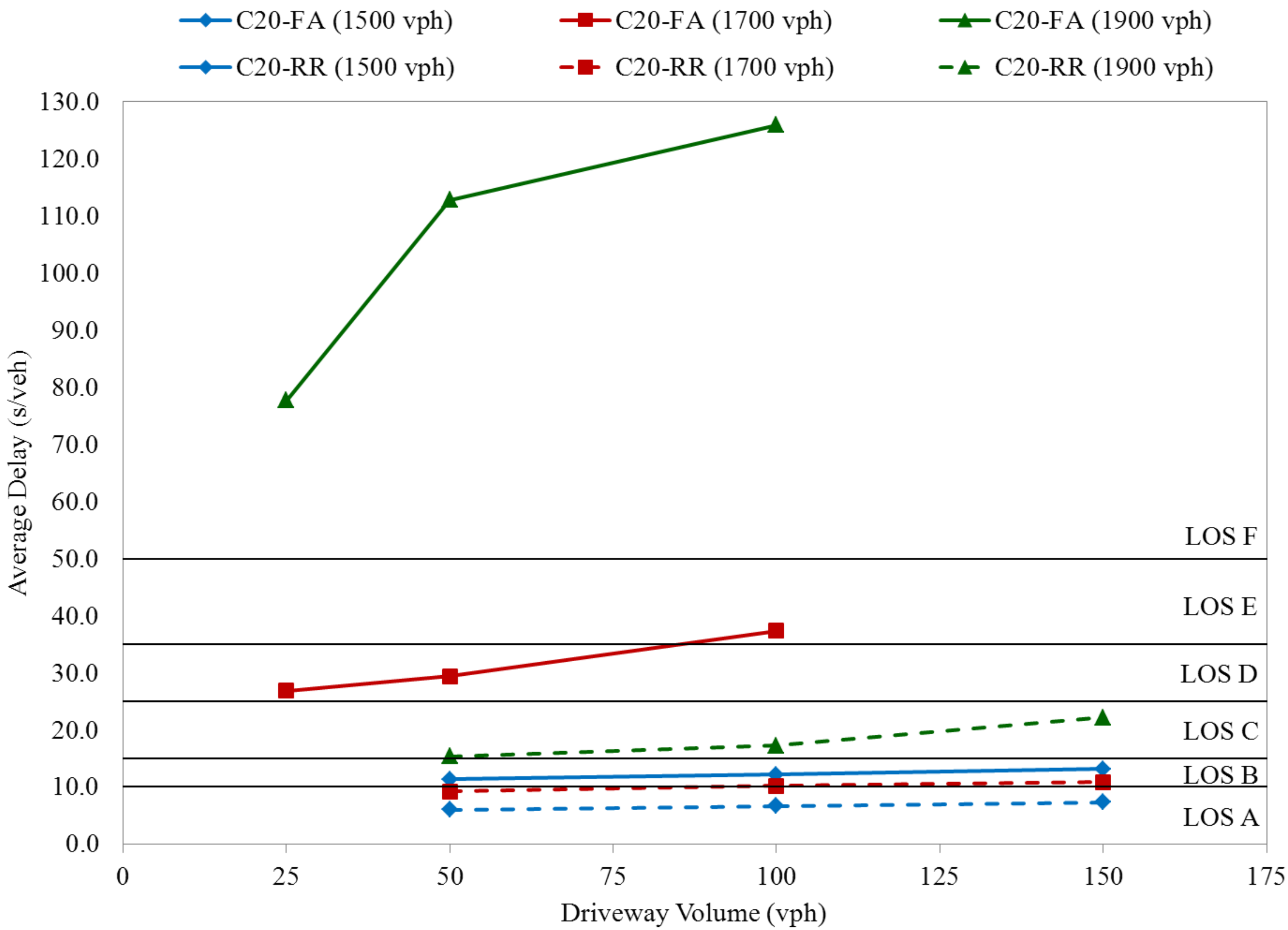

Figure 6.18 Average Delay for All Driveway Movements for Cases C20-FA and C20-RR

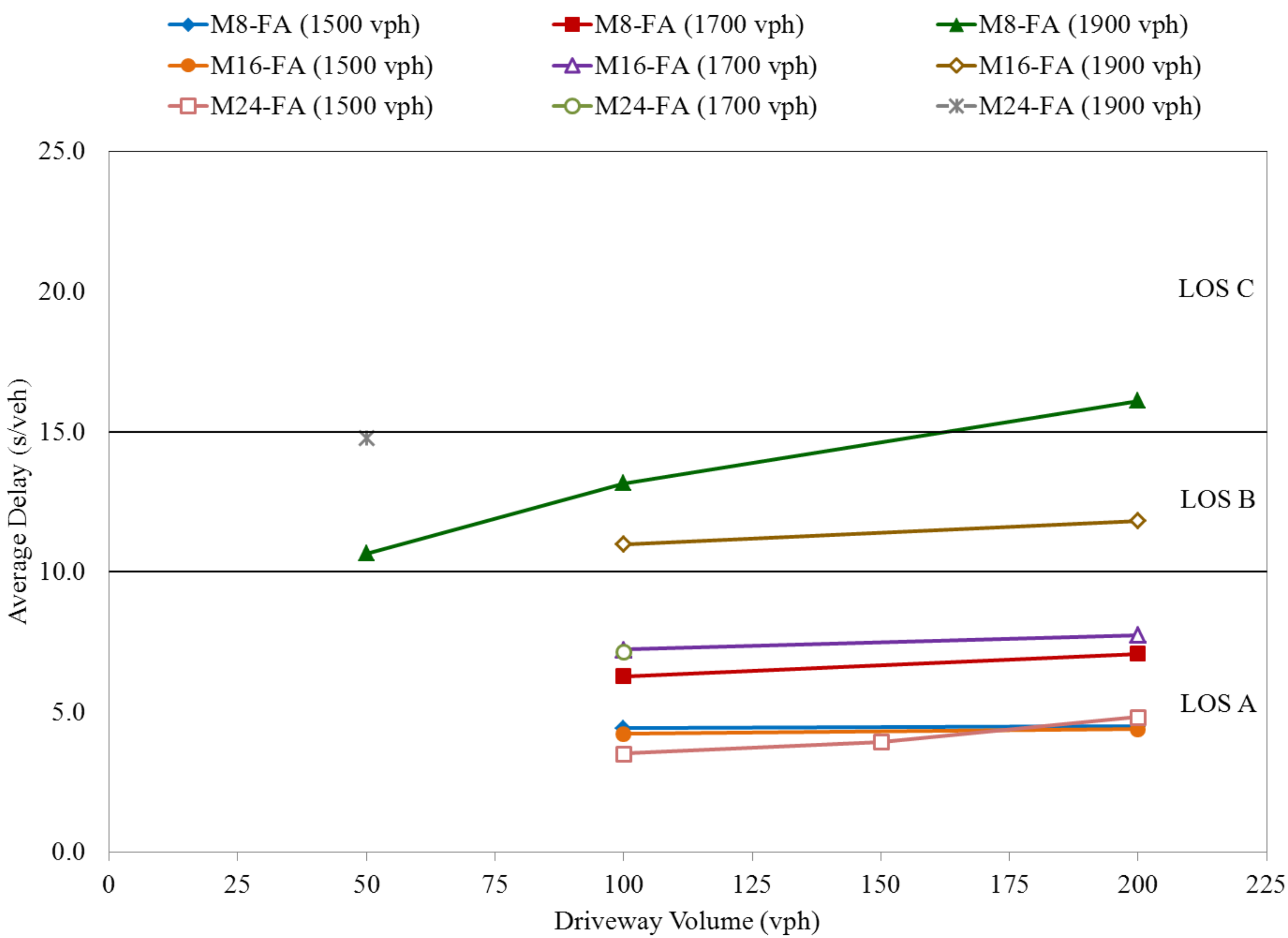

Figure 6.19 Average Delay for All Driveway Movements for Cases M8-FA, M16-FA, and M24-FA

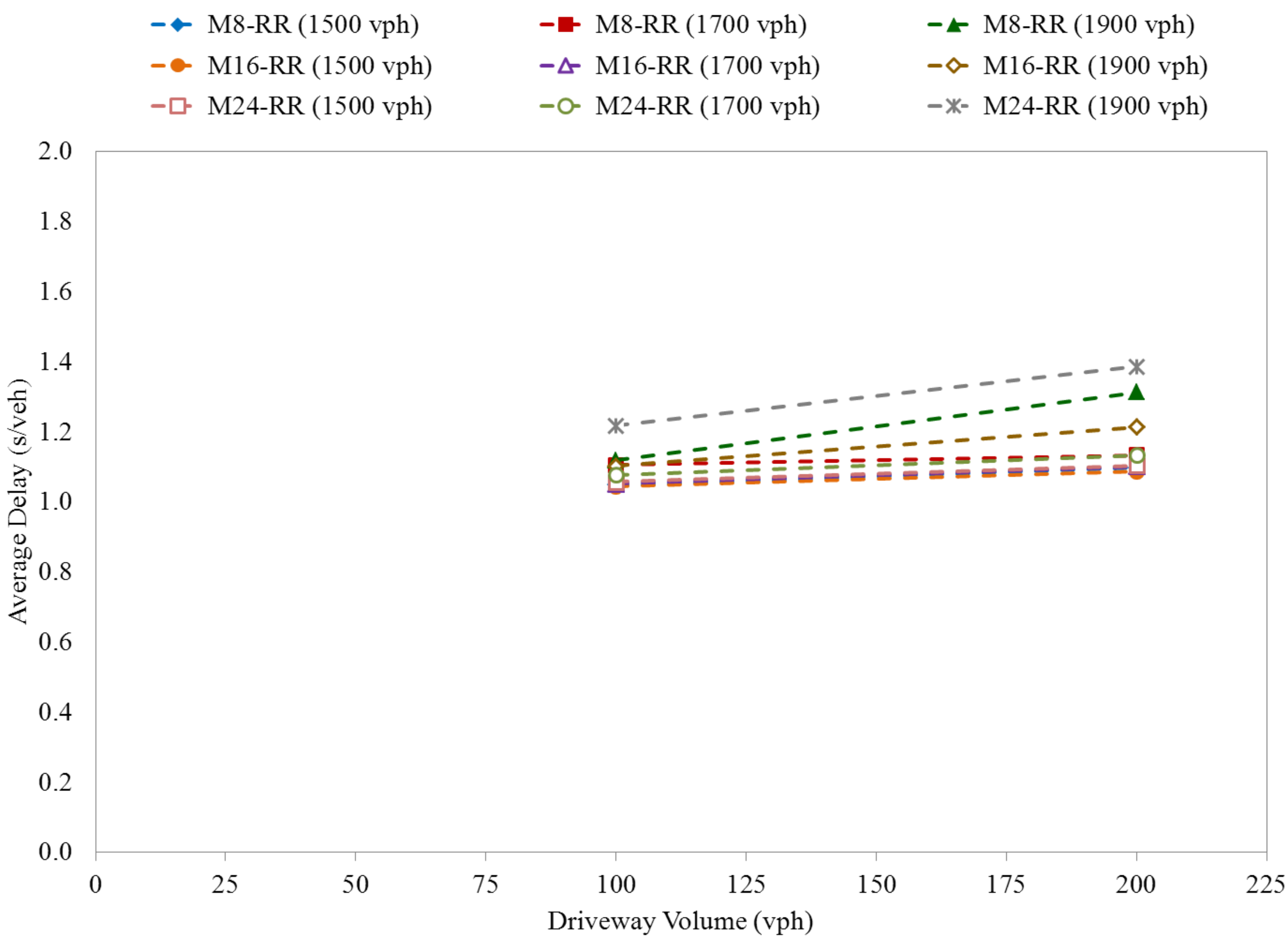

Figure 6.20 Average Delay for All Driveway Movements for Cases M8-RR, M16-RR, and M24-RR

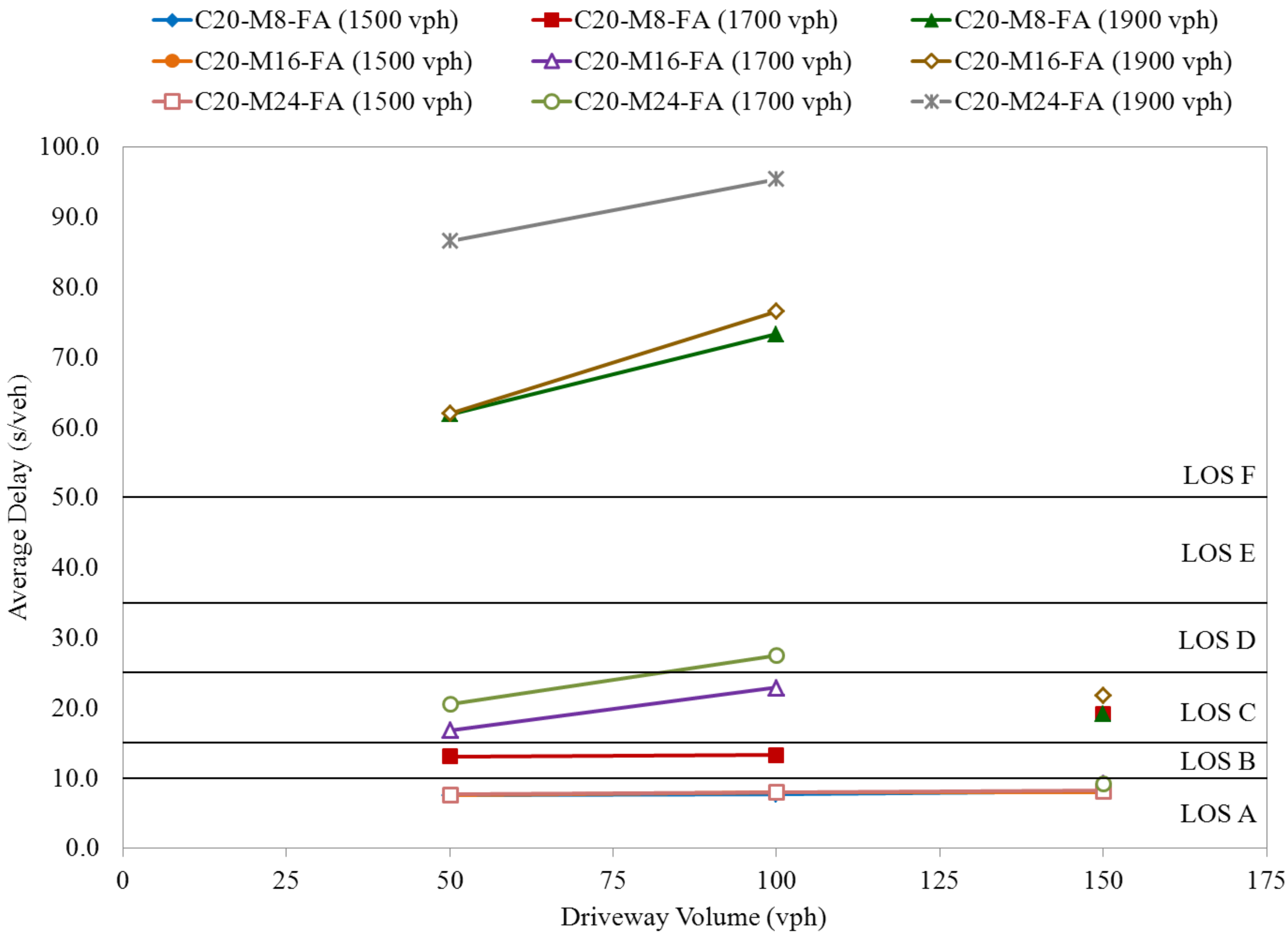

Figure 6.21 Average Delay for All Driveway Movements for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

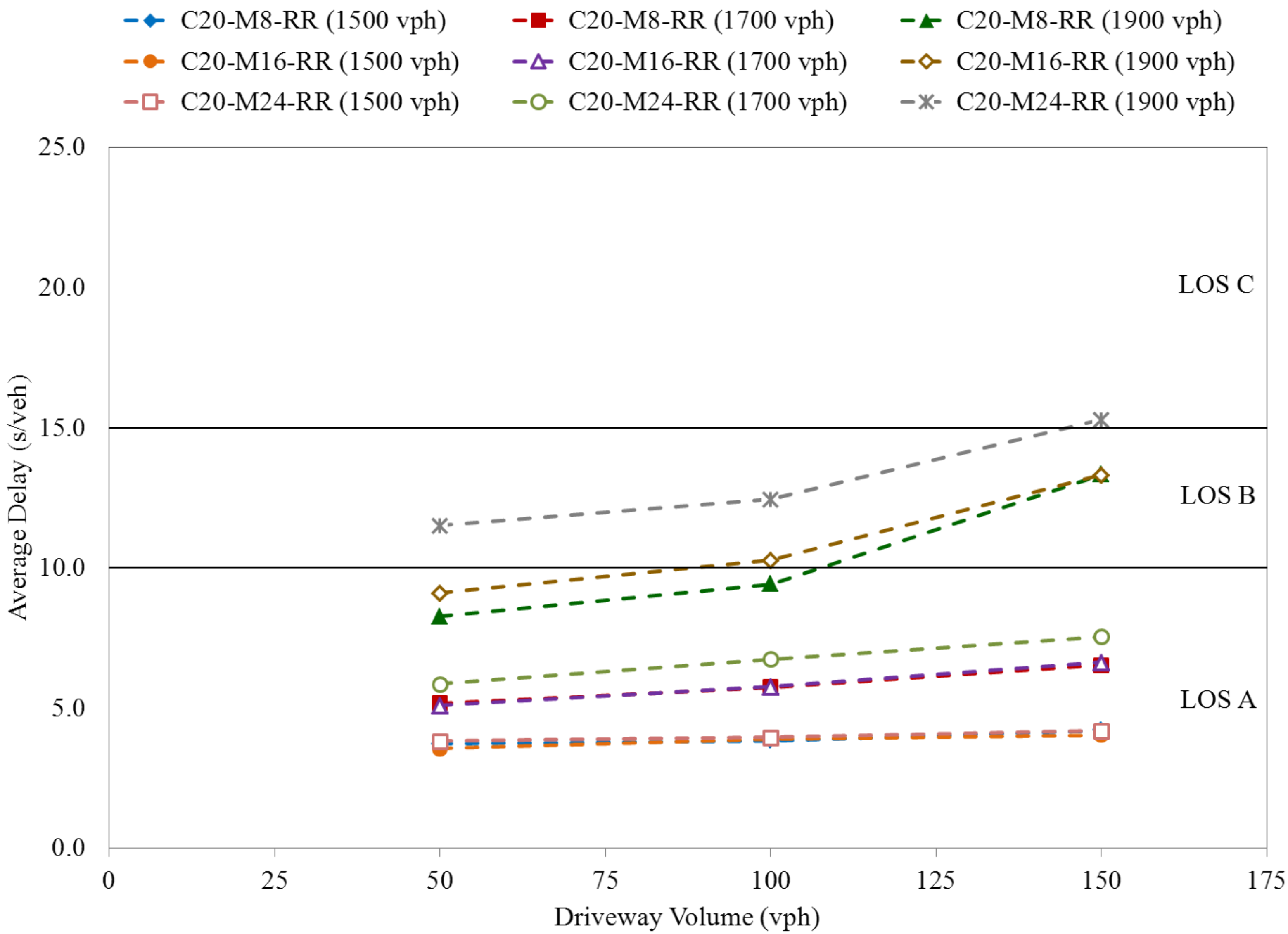

Figure 6.22 Average Delay for All Driveway Movements for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

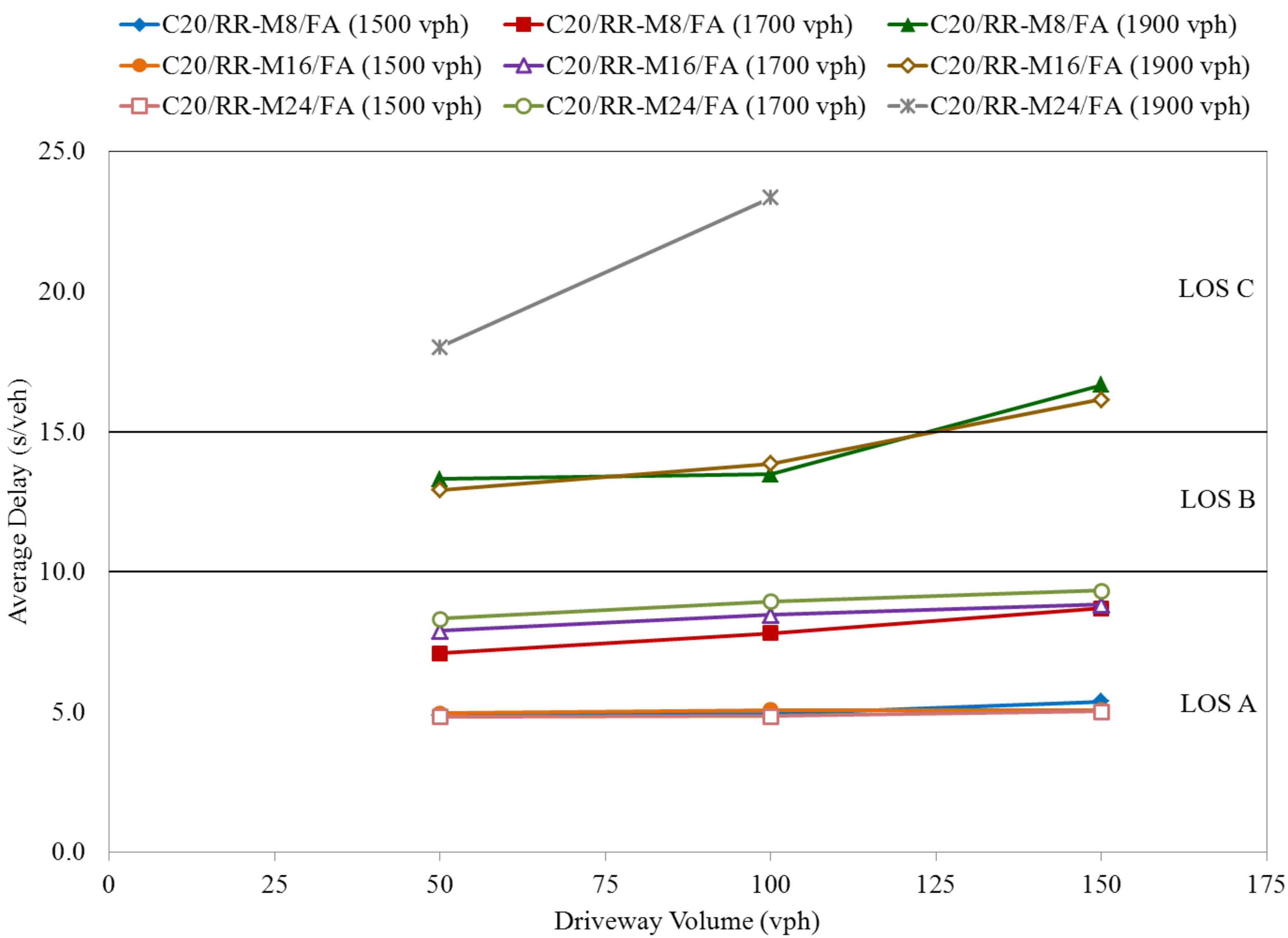

Figure 6.23 Average Delay for All Driveway Movements for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.2 Comparison of Average Delays for All Outbound Driveway Movements

The next set of figures from 6.24 to 6.29 show delays for only out-bound traffic from all driveways. The following are the key observations.

- For case C20-FA (20 corner full-access driveways), with medium and high mainline volume and across all driveway volumes, the average outbound driveway delay was at LOS E or worse (figure 6.24). For corresponding cases with right-in/out (RR) driveways, the LOS was C or better across all driveway and mainline volumes. The full-access case at low mainline volume across all driveway volumes had delays lower than right-in/out cases at high mainline volumes.
- For all the cases modeled with only midblock (M) full-access (FA) driveways, the LOS was B or better for all low and medium mainline volumes. With high mainline volumes, the outbound LOS was at D or worse (figure 6.25).
- For all the cases modeled with only midblock (M) right-in/out (RR) driveways, the LOS was B or better for all cases except M24-RR (all driveway volumes) and M16-RR (at 200 vphpd) at high mainline volume at LOS C (figure 6.26).
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, the LOS was B or better for all cases at low mainline volumes (figure 6.27). With medium mainline volume the LOS ranged from C to E with increasing outbound delays with increasing driveway volumes. All high volume cases had outbound delays in the range of LOS F.
- For cases with both corner (C) and midblock (M) right-in/out (RR) driveways, the LOS was B or better across all cases except high driveway volumes (150 vphpd) in all high

mainline cases with LOS C and also for driveway volumes 50-100 vphpd in medium mainline case (figure 6.28).

- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, all cases had LOS C or better except at high midblock density (24 driveways) across all driveway volumes and at medium midblock density (16 driveways) with 150 vphpd, the outbound delay was at LOS E (figure 6.29).

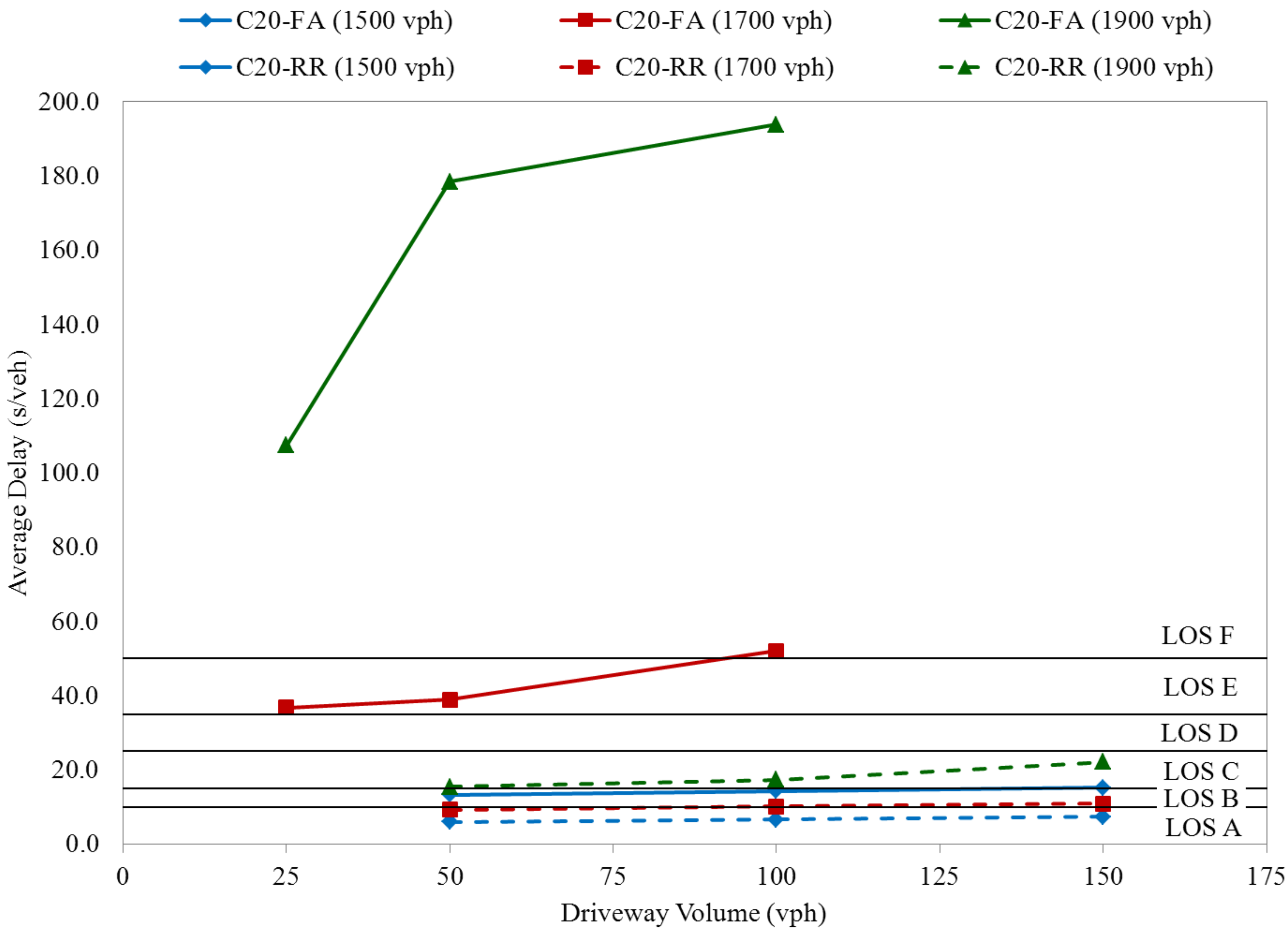

Figure 6.24 Average Delay for All Outbound Driveway Movements for Cases C20-FA and C20-RR

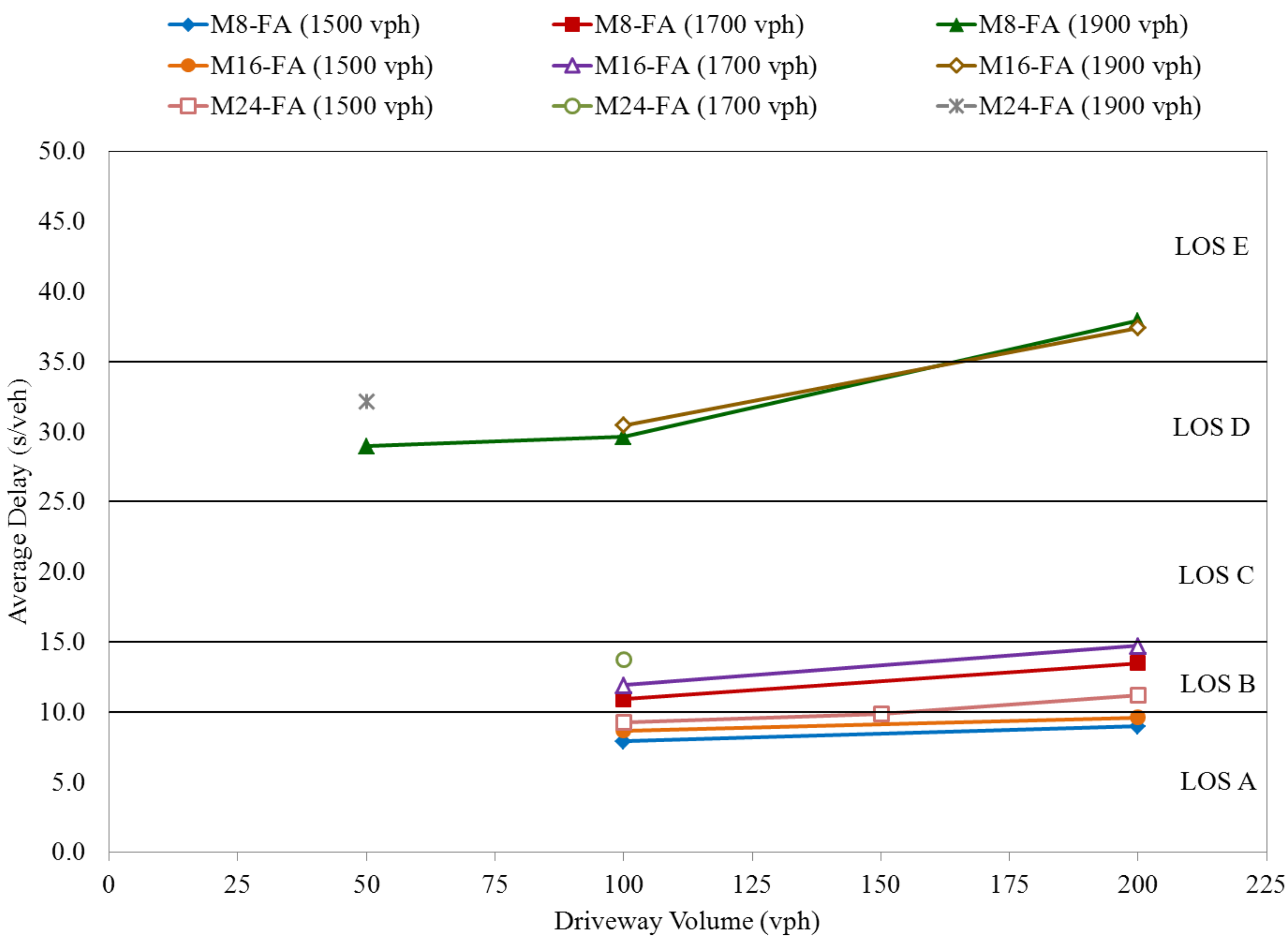

Figure 6.25 Average Delay for All Outbound Driveway Movements for Cases M8-FA, M16-FA, and M24-FA

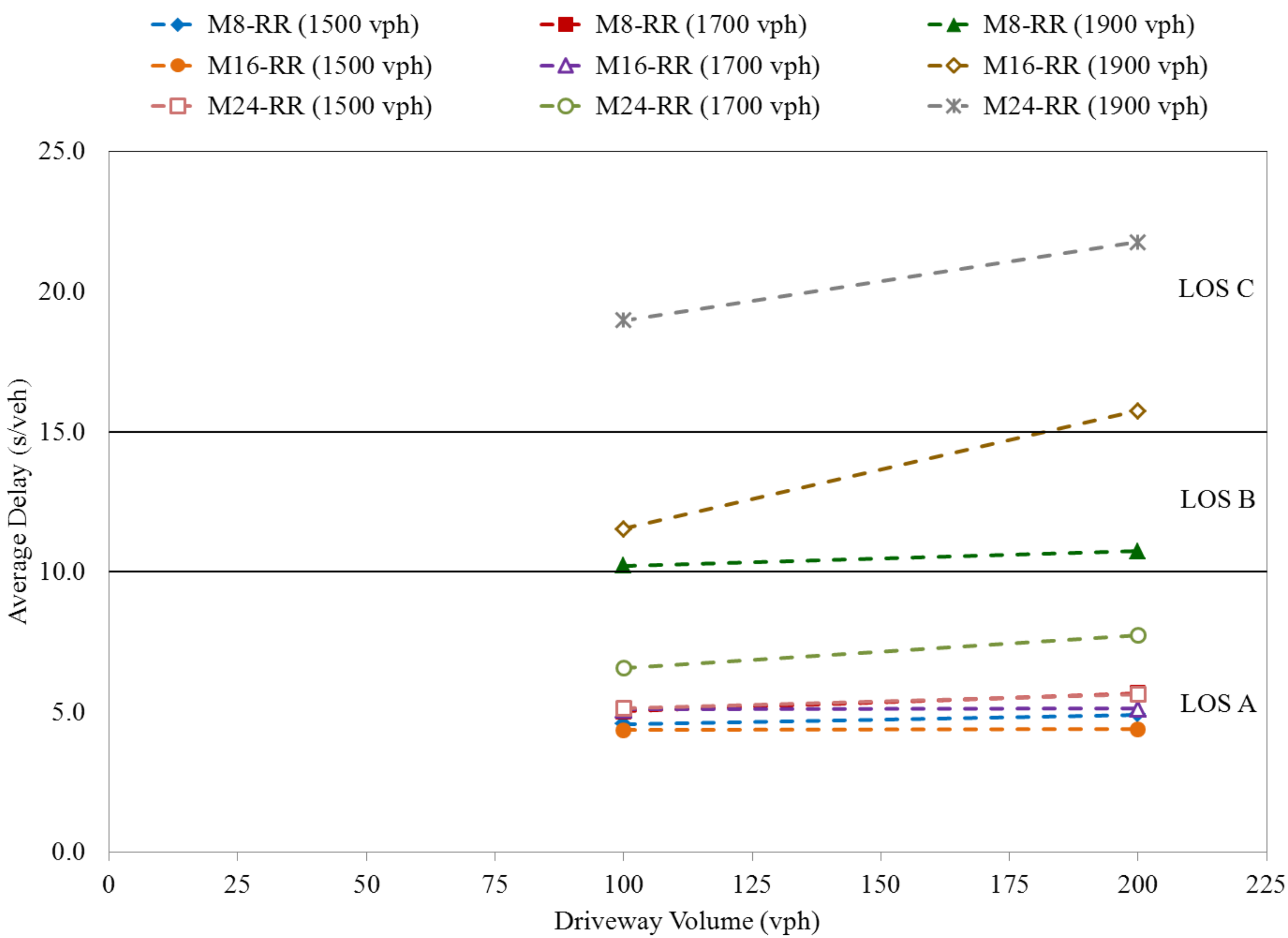

Figure 6.26 Average Delay for All Outbound Driveway Movements for Cases M8-RR, M16-RR, and M24-RR

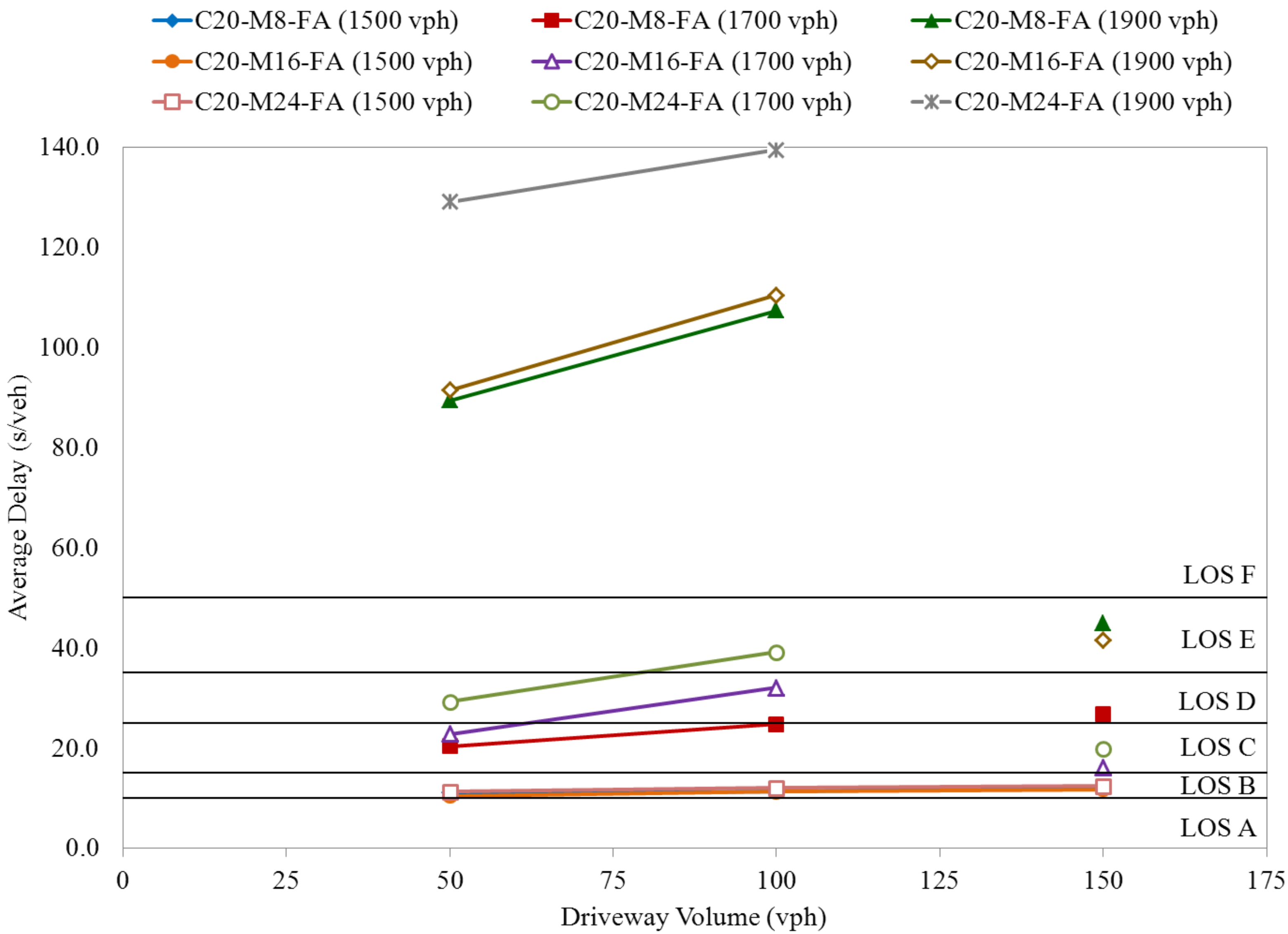

Figure 6.27 Average Delay for All Outbound Driveway Movements for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

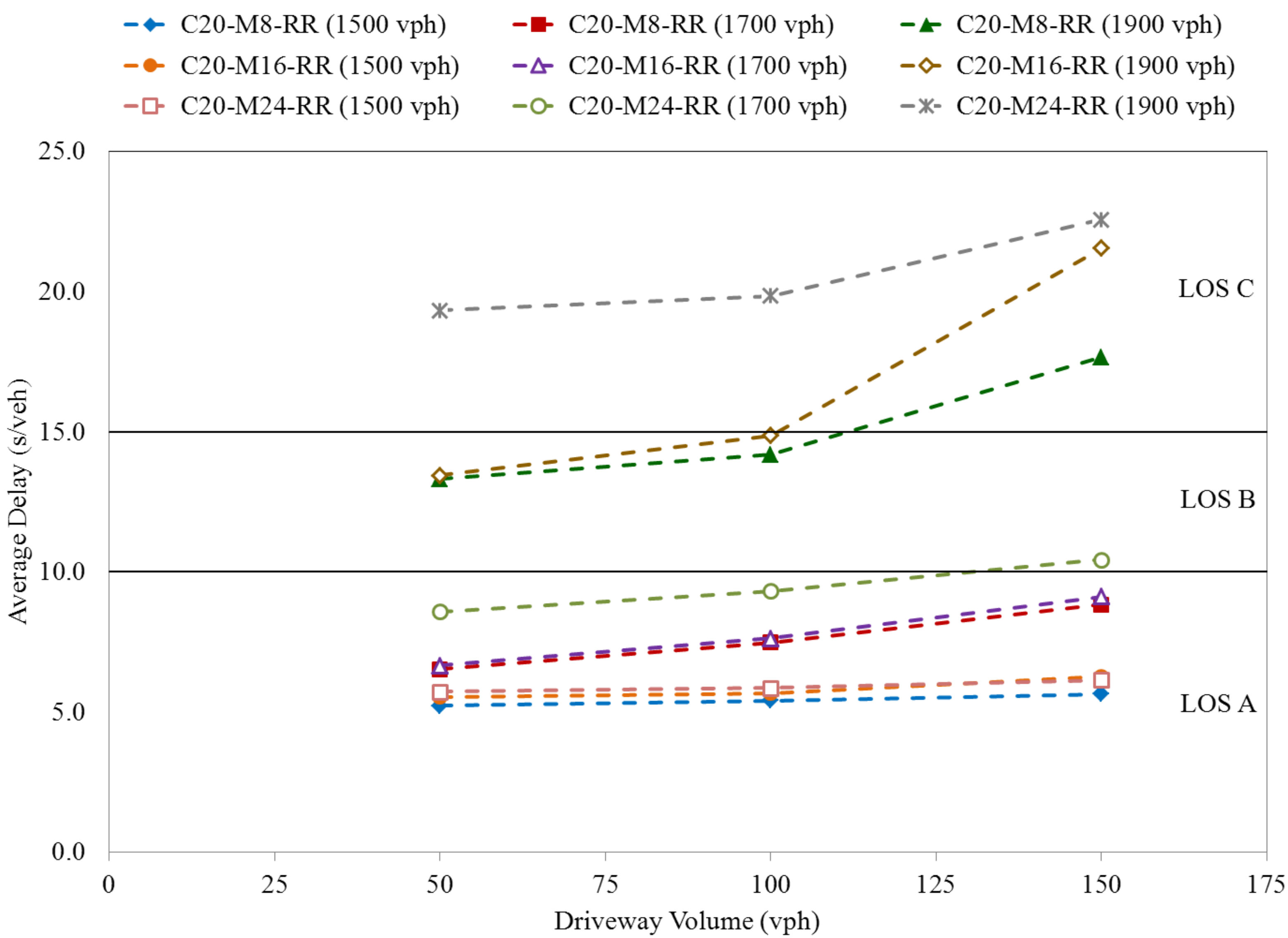

Figure 6.28 Average Delay for All Outbound Driveway Movements for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

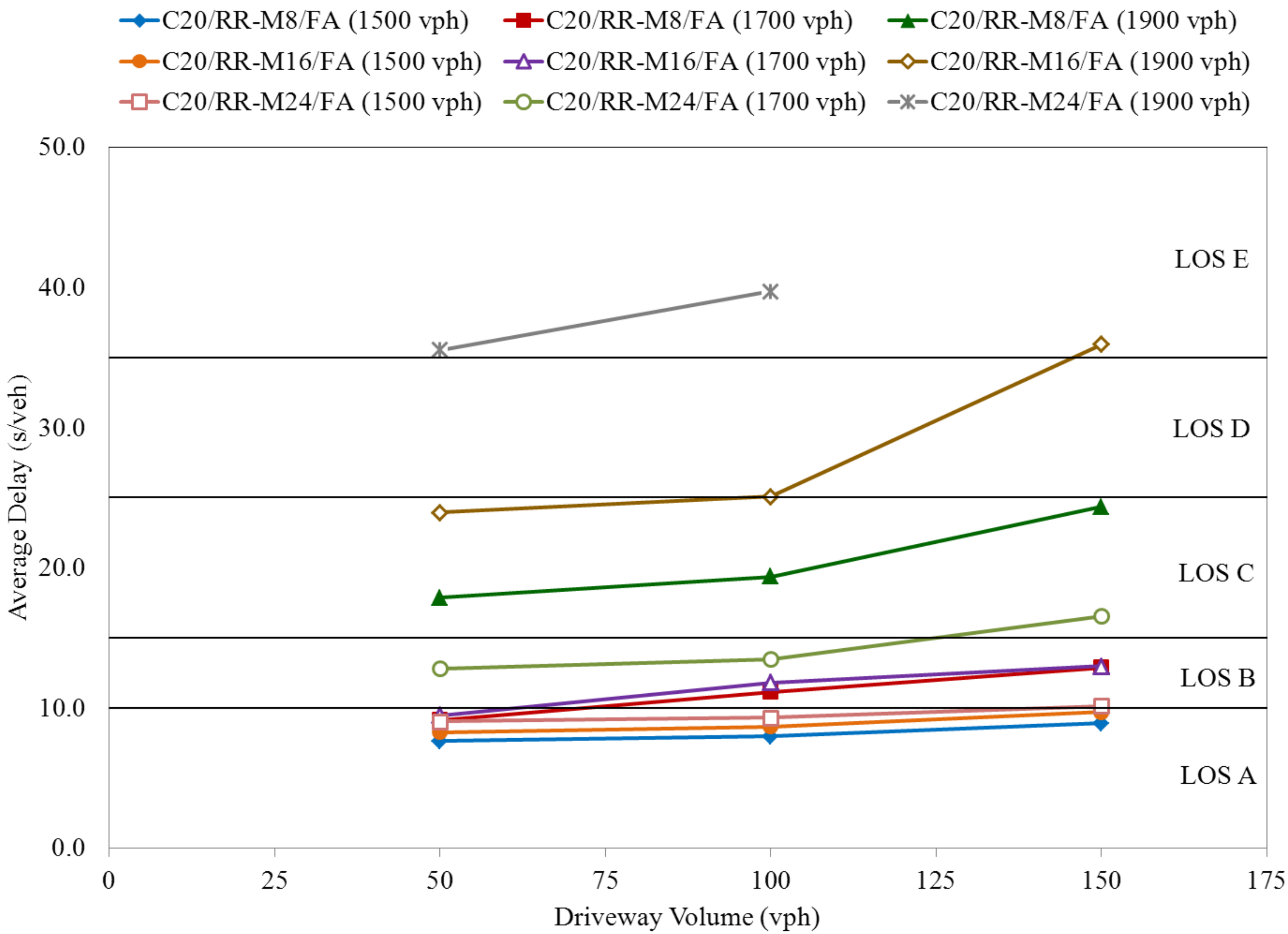

Figure 6.29 Average Delay for All Outbound Driveway Movements for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.3 Comparison of Average Delays for All Right-Out Driveway Movements

In figures 6.30 to 6.33, the average delays (s/veh) and corresponding LOS are shown for all right-out driveway movements. The results are discussed for only full-access cases because all right-out results for right-in/out driveways are essentially the same as outbound delays as shown in the previous set of graphs.

- For case C20-FA (20 corner full-access driveways), all right-out delays are at LOS A for low mainline volume, from B to D for medium mainline volume with higher delays with increasing driveway volumes, and LOS F for all high mainline volume (figure 6.30). Compared to outbound delays for all full-access cases at LOS E or worse, the right-out delays are lower than overall outbound delays.
- For all the cases modeled with only midblock (M) full-access (FA) driveways, the LOS was C or better except for M16-FA at high mainline volume and 200 vphpd at LOS D (figure 6.31). The delays for corresponding overall outbound movements were higher than right-out delays.
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, the LOS was C or better across all low and medium mainline volumes (figure 6.32). With high mainline volumes, the LOS was F for up to 100 vphpd, and was D or better for cases with difference corner and driveway volumes (C25, M150).
- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, all cases had LOS C or better except at high midblock density (24 driveways) with 100 vphpd at LOS D (figure 6.33).

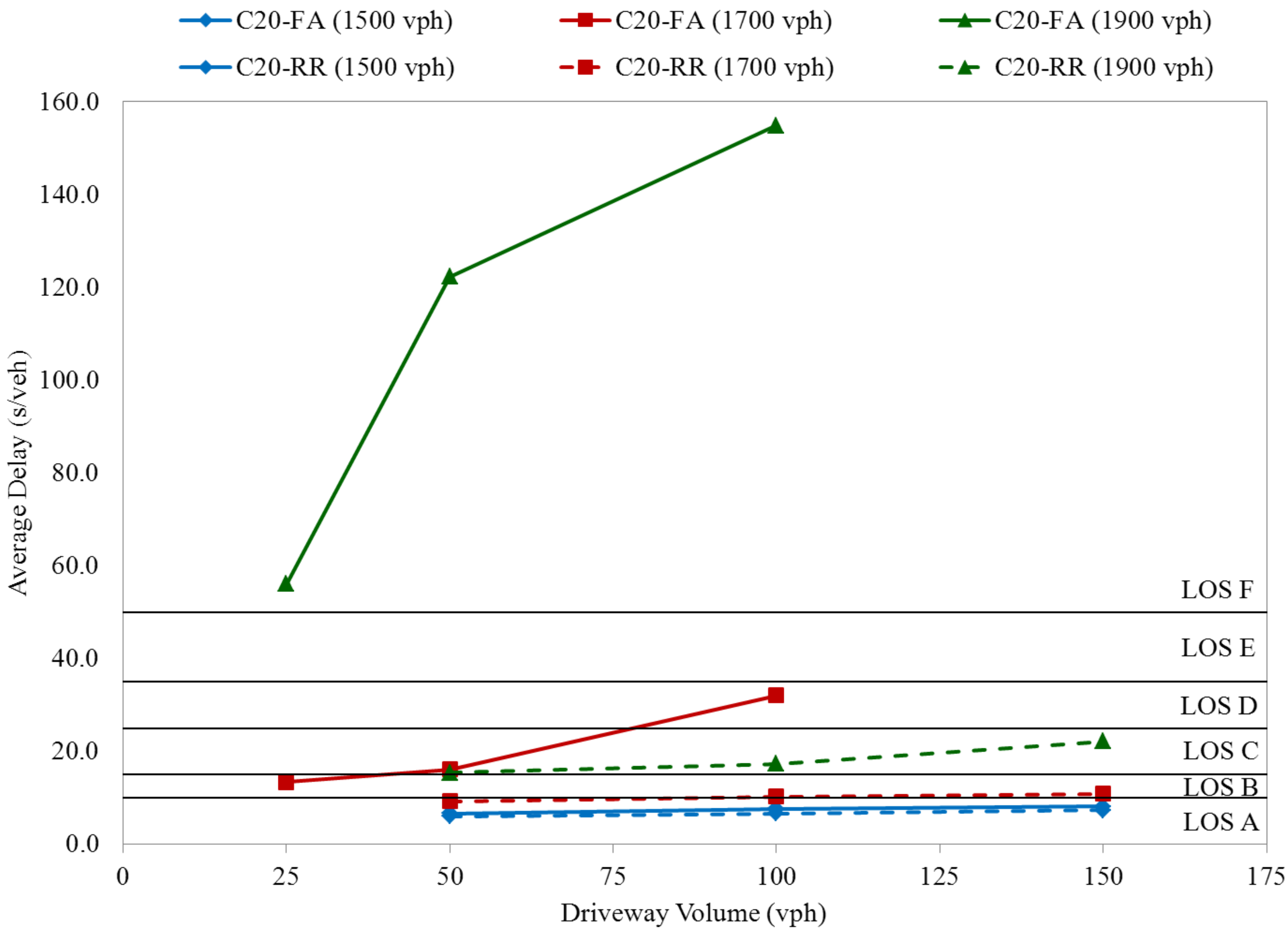

Figure 6.30 Average Delay for All Right-Out Driveway Movements for Cases C20-FA and C20-RR

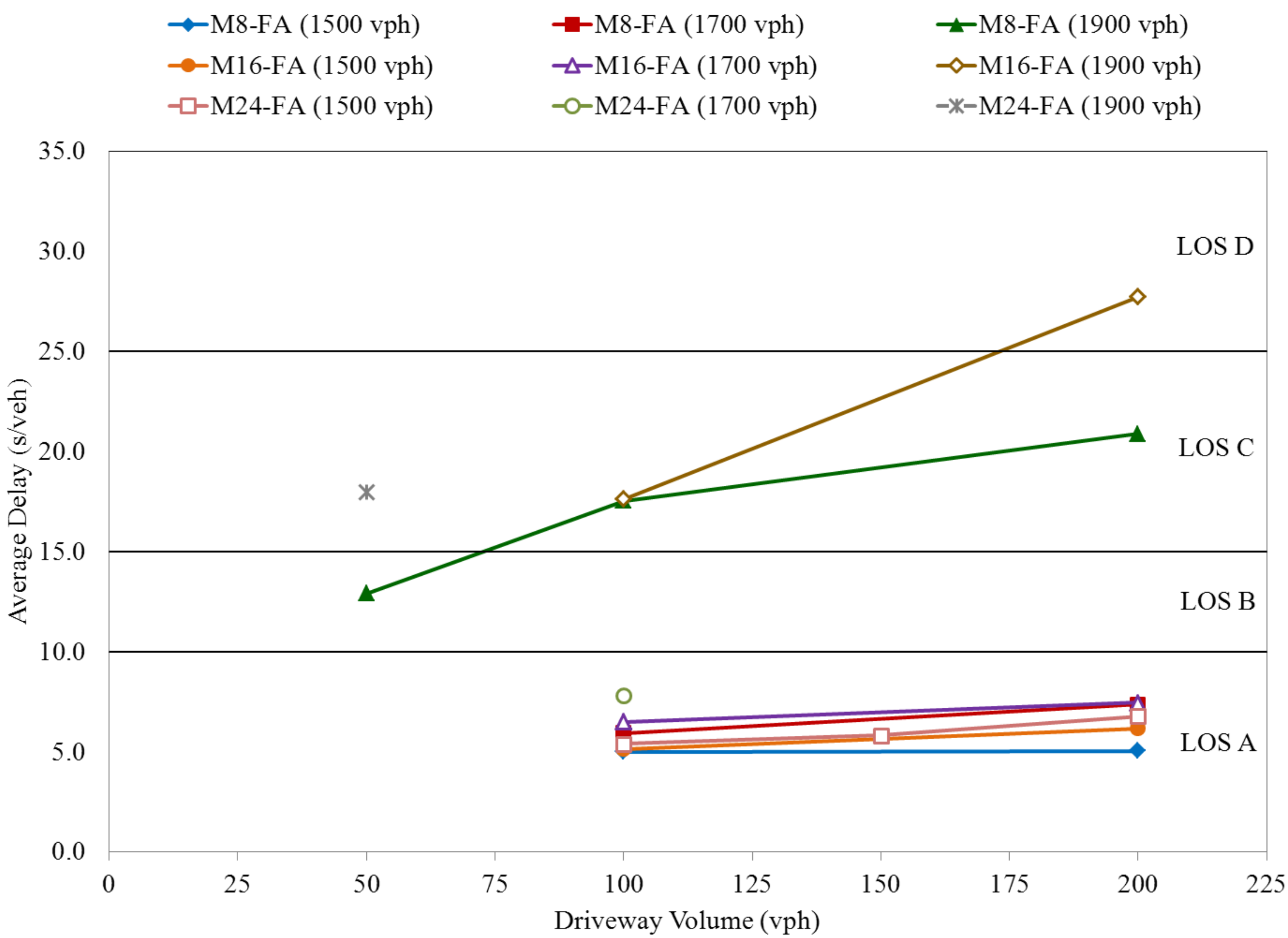

Figure 6.31 Average Delay for All Right-Out Driveway Movements for Cases M8-FA, M16-FA, and M24-FA

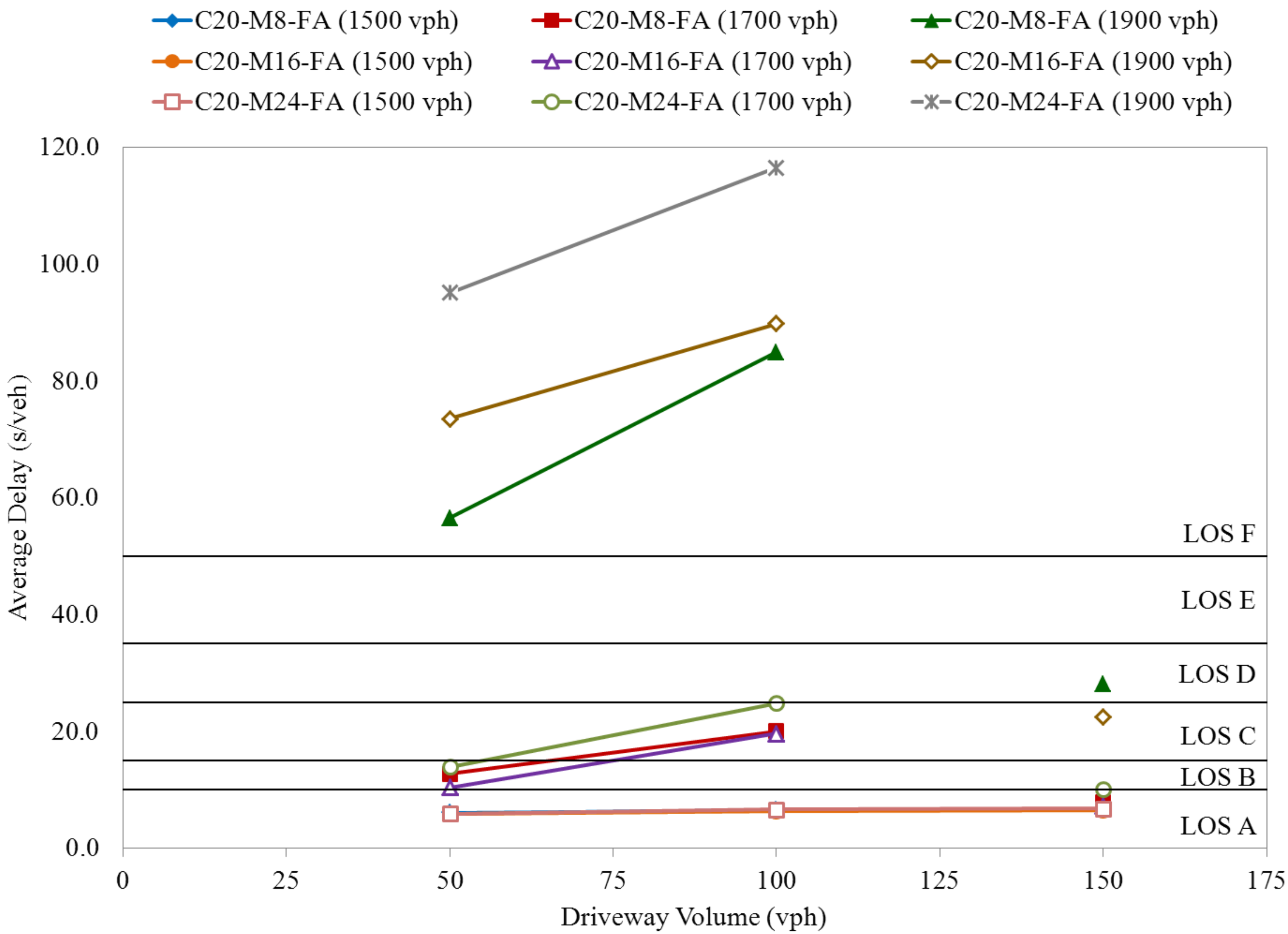

Figure 6.32 Average Delay for All Right-Out Driveway Movements for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

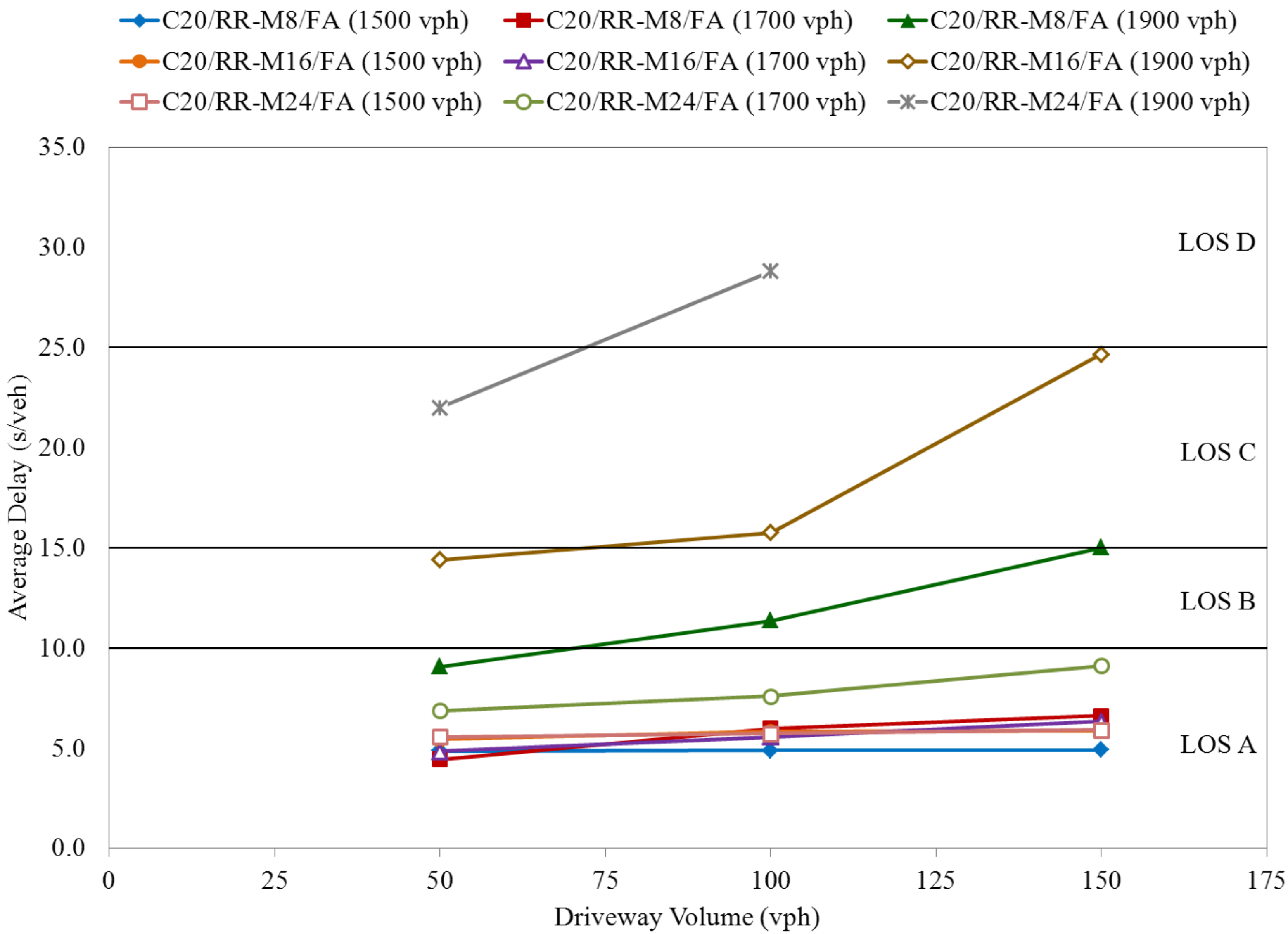

Figure 6.33 Average Delay for All Right-Out Driveway Movements for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.4 Comparison of Average Delays for All Left-Out Driveway Movements

Left-out delays for all cases with full-access driveways are shown in figures 6.34 to 6.37, and key observations are described below.

- For case C20-FA (20 corner full-access driveways), all left-out delays are at LOS C for low mainline volume, and at LOS F for medium and high mainline volumes, which for all scenarios are higher than corresponding right-out delays (figure 6.34).
- For all the cases modeled with only midblock (M) full-access (FA) driveways, the LOS was C or better for low and medium mainline volumes, and D or worse for high mainline volume cases (figure 6.35). The delays for corresponding right-out movements were lower than left-out movements.
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, the LOS was C for all low mainline volume cases, and D or worse for all medium and high mainline volume cases (figure 6.36). The delays for corresponding right-out movements were lower than left-out movements.
- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, the LOS was C or better for all low and medium mainline volume cases, and D or worse for all high mainline volume cases (figure 6.37). The delays for corresponding right-out movements were lower than left-out movements.

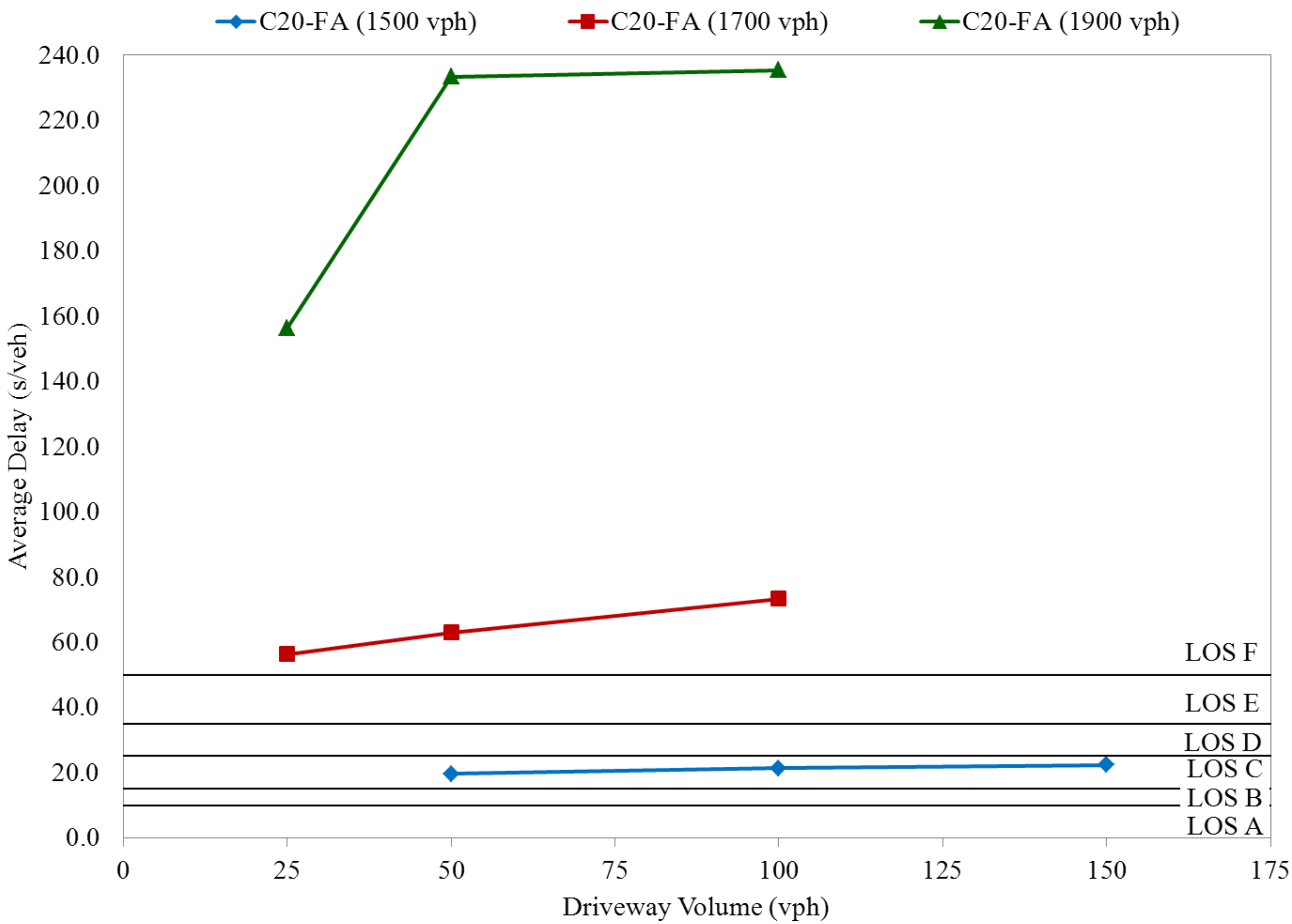

Figure 6.34 Average Delay for All Left-Out Driveway Movements for Cases C20-FA and C20-RR

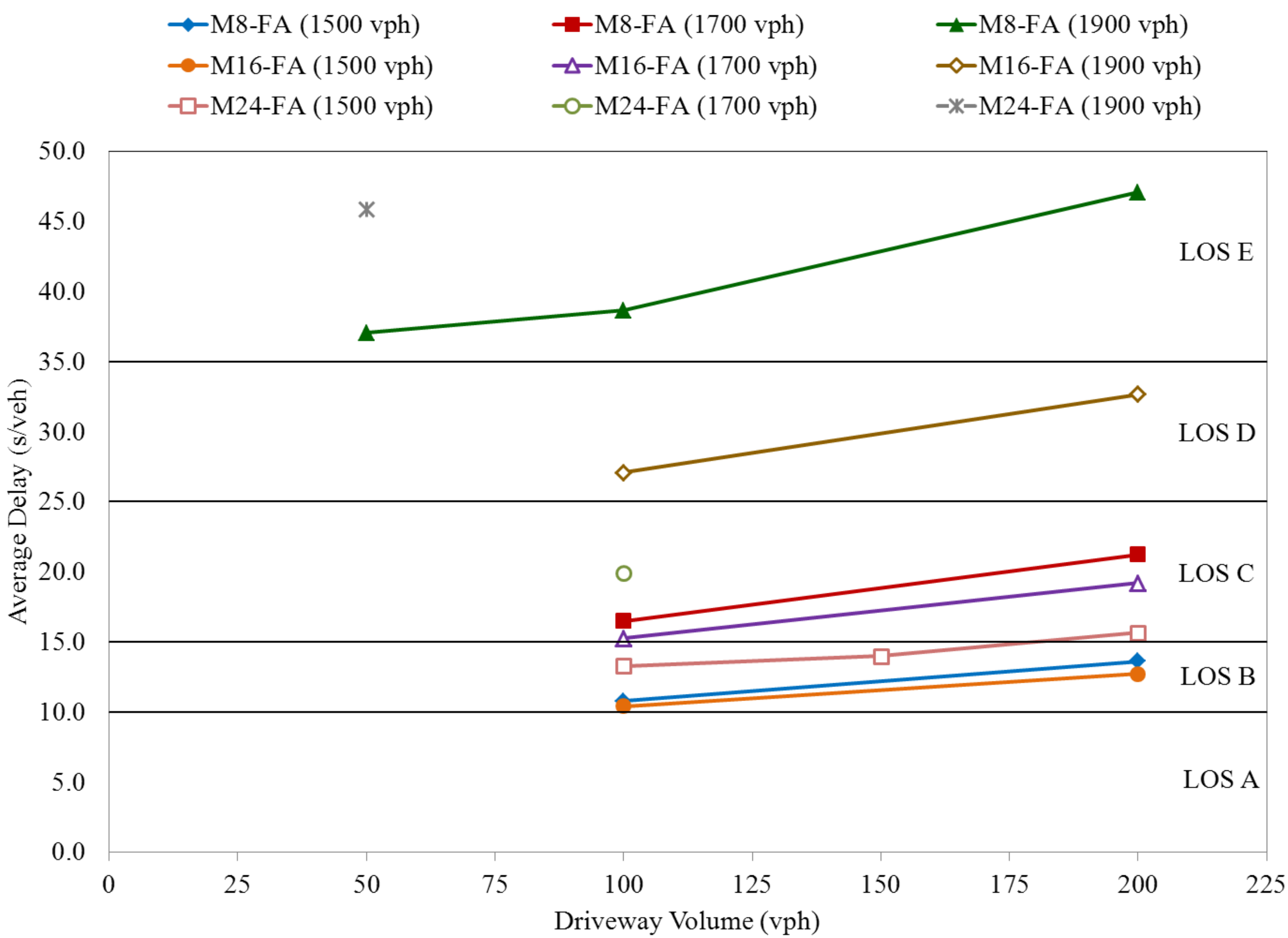

Figure 6.35 Average Delay for All Left-Out Driveway Movements for Cases M8-FA, M16-FA, and M24-FA

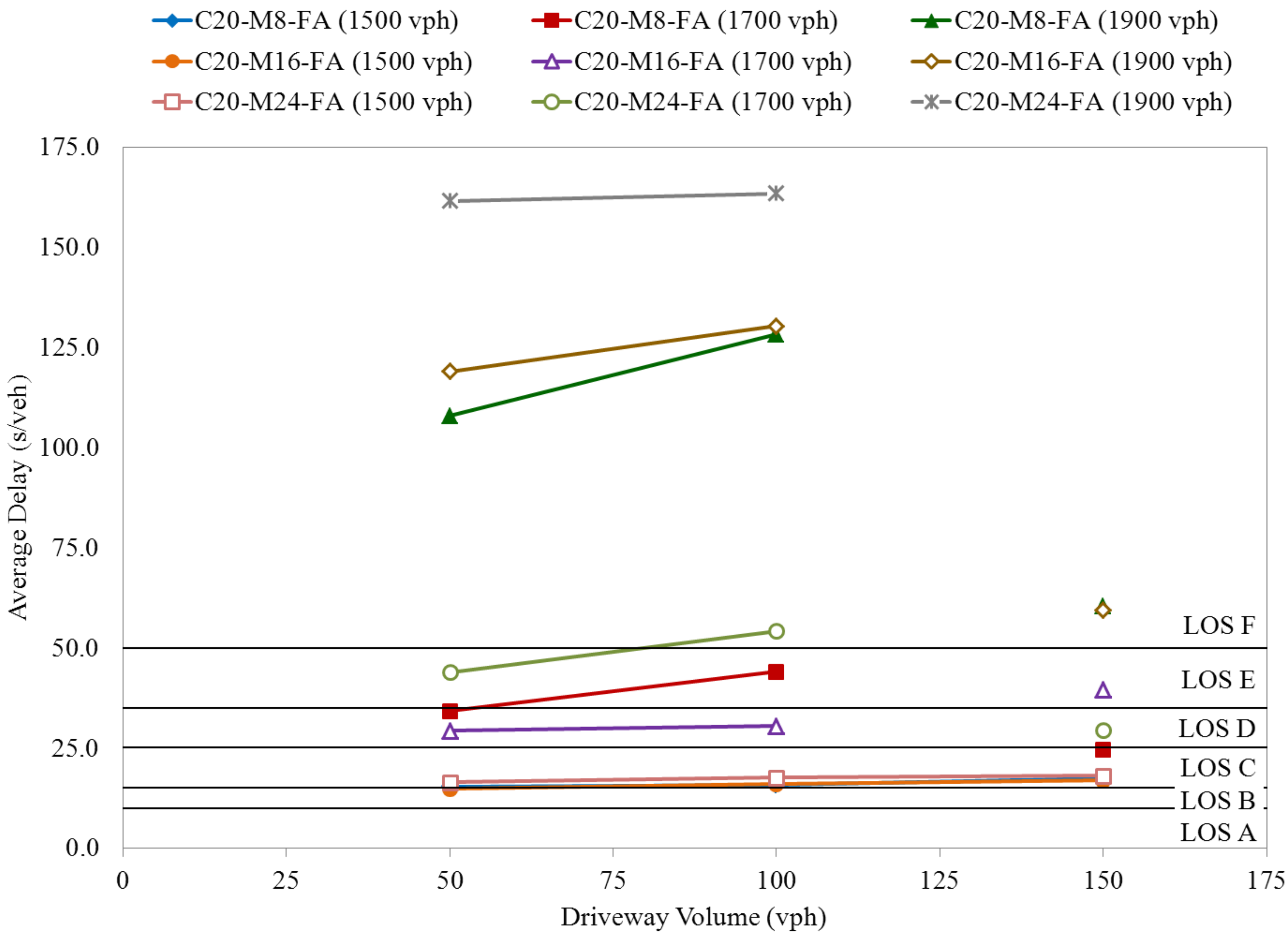

Figure 6.36 Average Delay for All Left-Out Driveway Movements for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

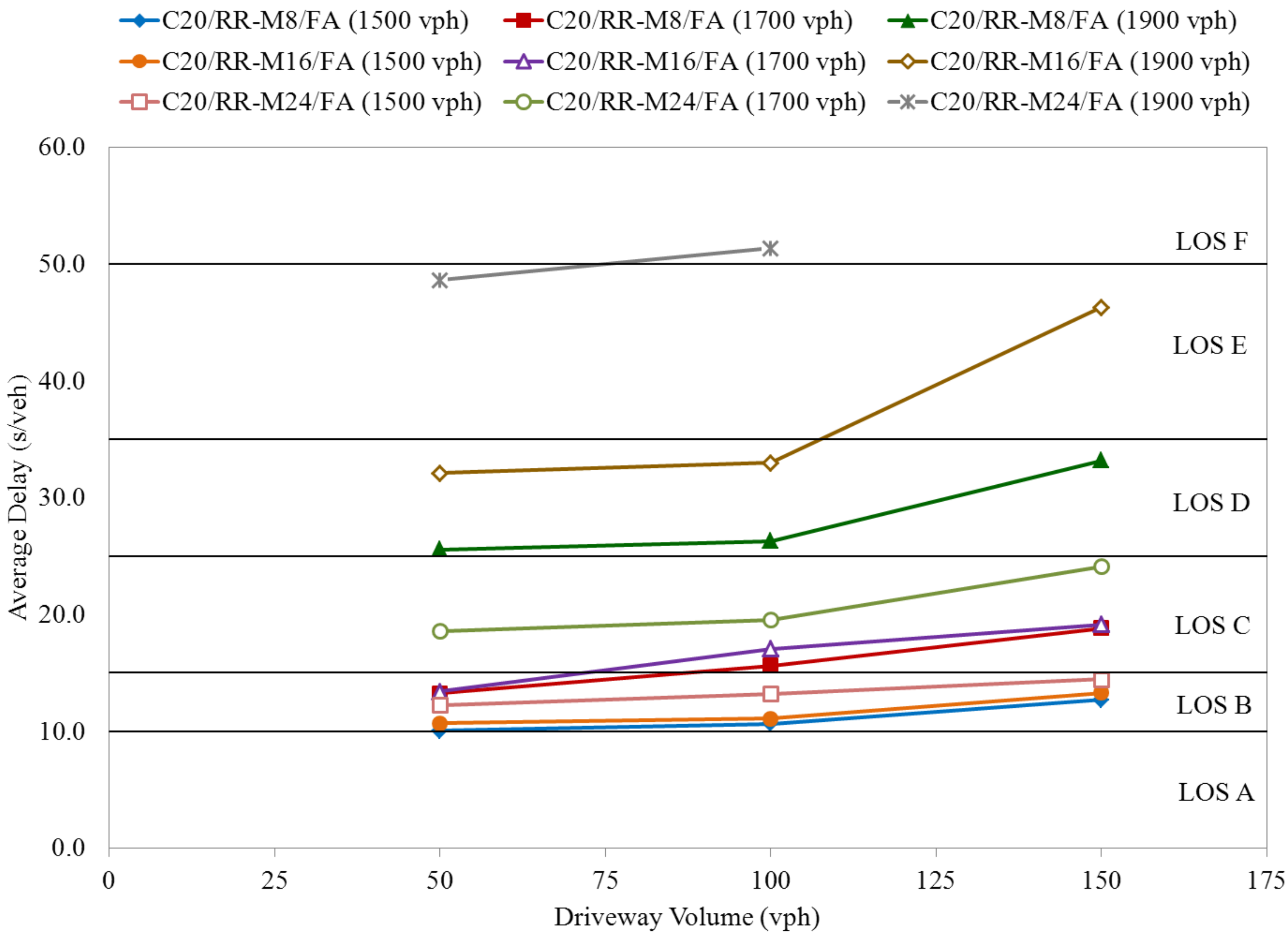

Figure 6.37 Average Delay for All Left-Out Driveway Movements for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.5 Comparison of Average Delays for All Left-In Driveway Movements from TWLTL

Figures 6.38 to 6.41 present the average left-in delay (s/veh) for vehicles waiting in the TWLTL to complete the turn. The main outcomes for all applicable cases are presented below.

- For case C20-FA (20 corner full-access driveways), all left-in delays (departure side only) are at LOS A for low, LOS B for medium, and LOS C for high mainline volumes across all driveway volumes (figure 6.38). The left-out delays at corresponding driveways were higher than left-in delays (at LOS C, F and F respectively for low, medium, and high mainline volumes).
- For all the cases modeled with only midblock (M) full-access (FA) driveways, all low mainline volume cases had left-in delays with LOS A, all medium mainline volume cases were at C, and all high volume cases were at LOS D or worse (figure 6.39). Corresponding left-out delays were higher.
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, all low mainline volume cases had left-in delays with LOS A, all medium mainline volume cases were at B, and all high volume cases were at LOS C (figure 6.40). Corresponding left-out delays were much higher (from LOS C to F).
- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, the LOS was A for all low mainline volume cases, LOS C or better for all medium mainline volume cases, and D or worse for all high mainline volume cases (figure 6.41). The delays for corresponding left-out movements were approximately the same except at low mainline volume cases where left-out delays were higher.

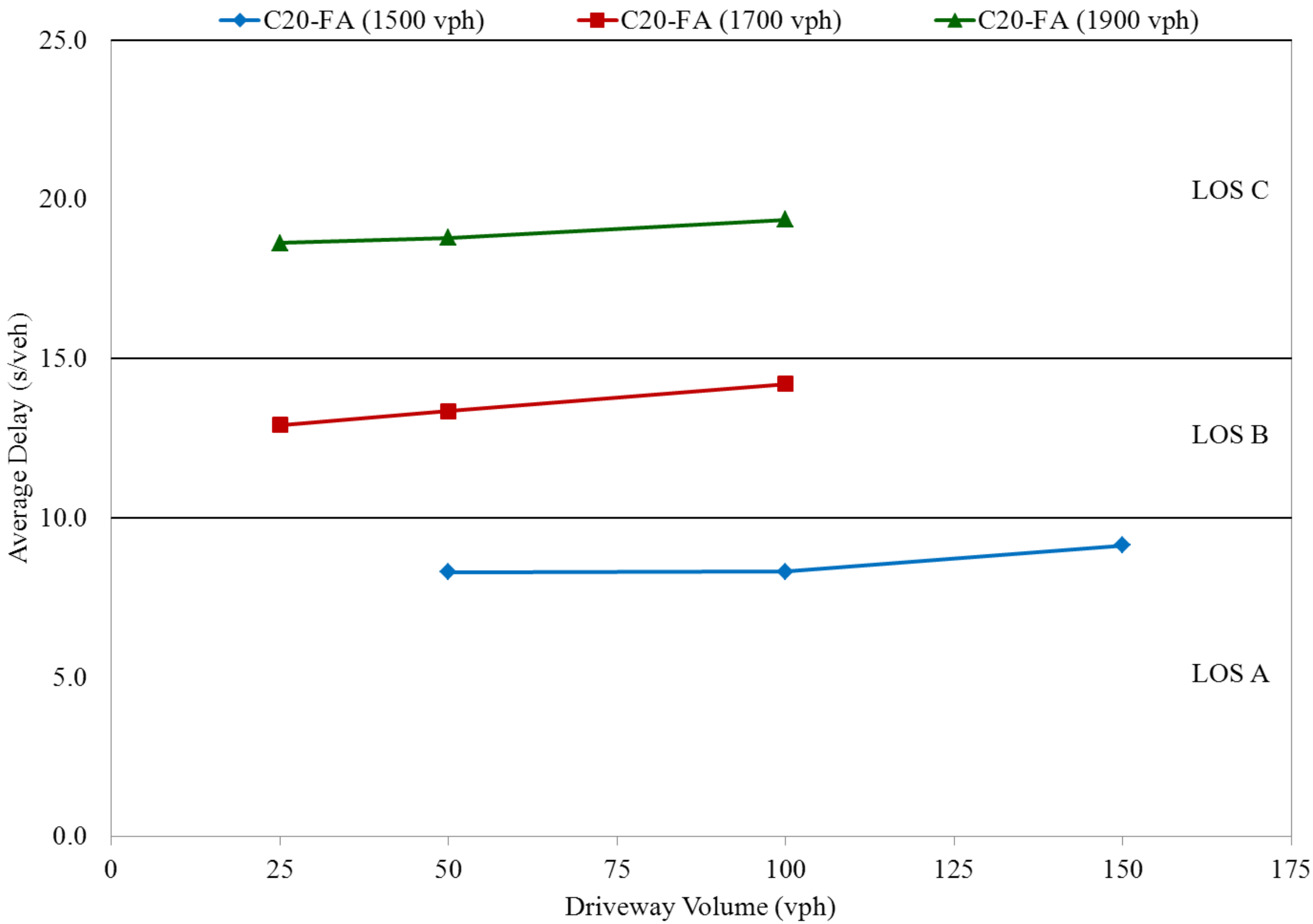

Figure 6.38 Average Delay for All Left-In Driveway Movements for Cases C20-FA and C20-RR

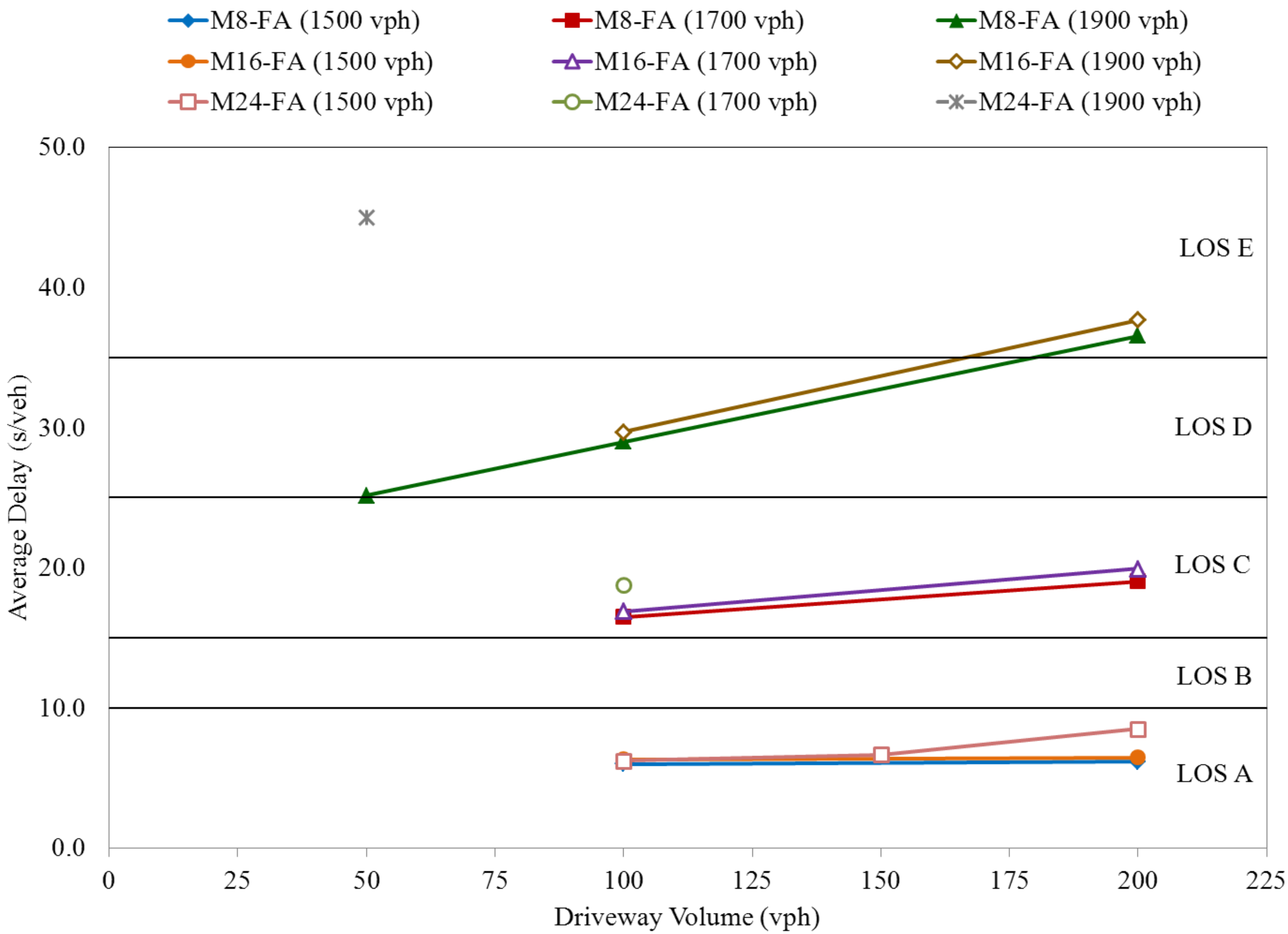

Figure 6.39 Average Delay for All Left-In Driveway Movements for Cases M8-FA, M16-FA, and M24-FA

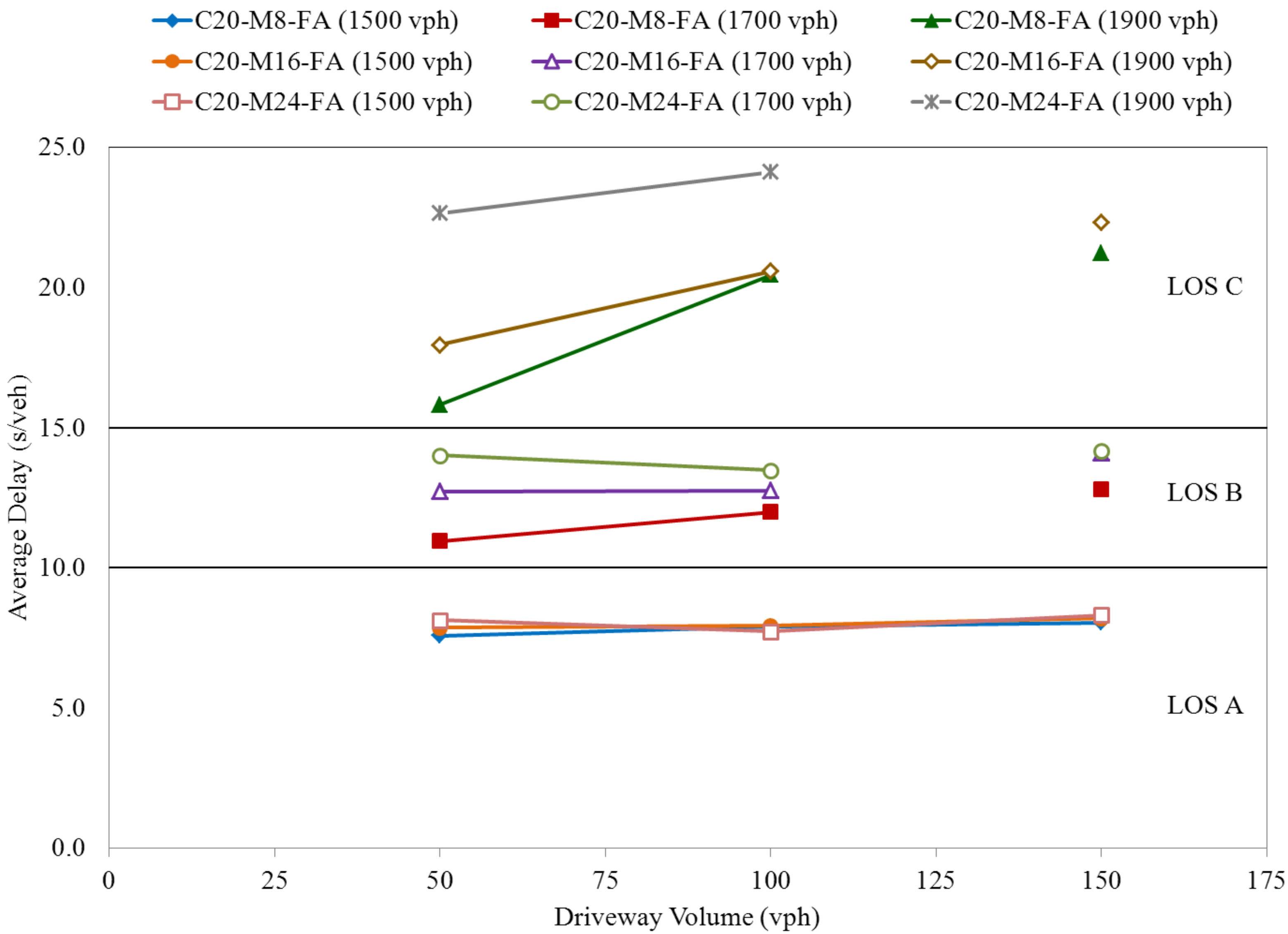

Figure 6.40 Average Delay for All Left-In Driveway Movements for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

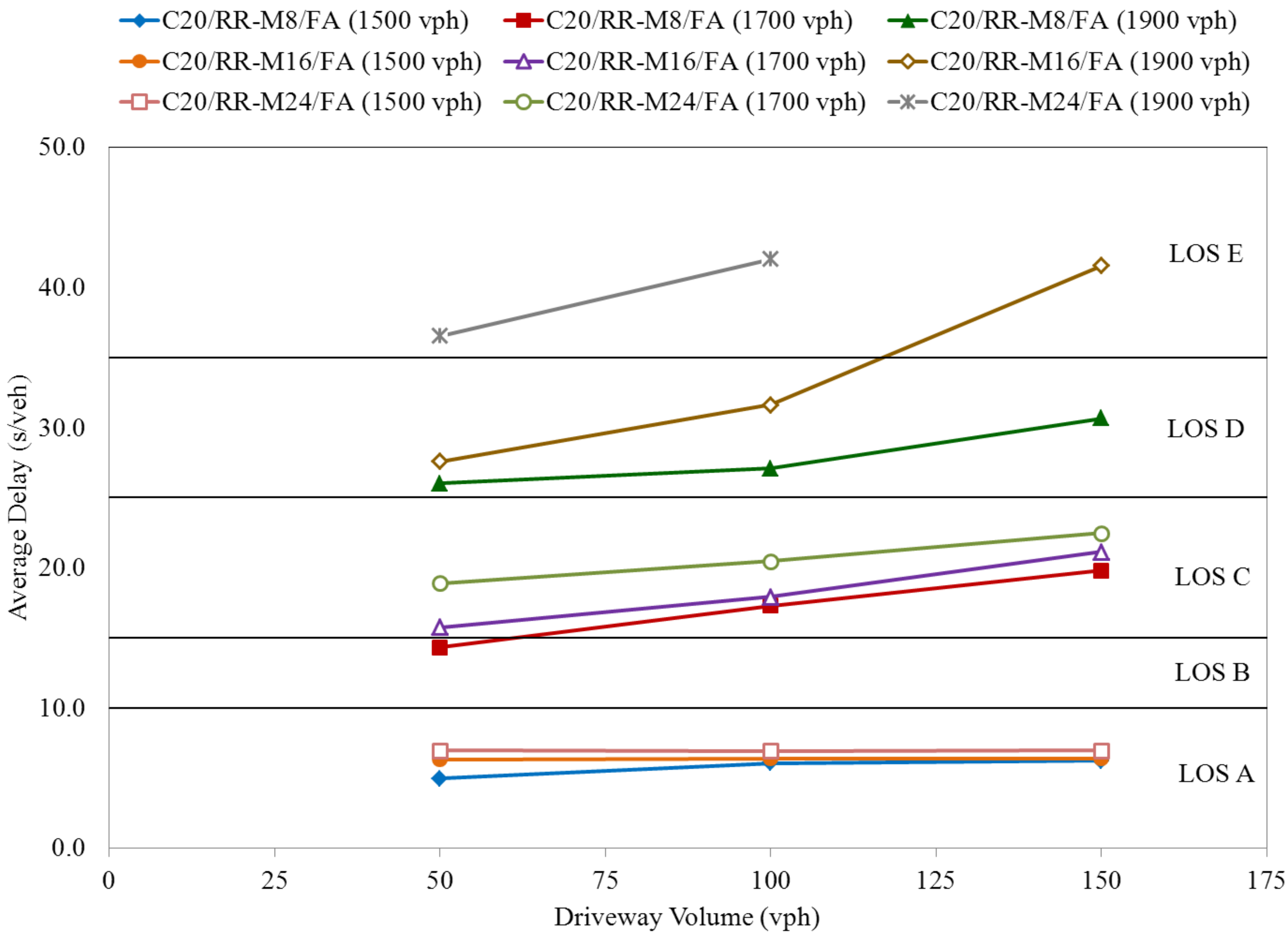

Figure 6.41 Average Delay for All Left-In Driveway Movements for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.6 Comparison of Average Delays for All Driveway-related Movements from TWLTL onto the Mainline

Figures 6.42 to 6.44 present the average delay (s/veh) for all driveway-related movements in TWLTL (where applicable) when the vehicles were waiting to merge onto the mainline. Vehicles turning left-out from the corner driveways did not have the TWLTL and had to directly merge into the desired mainline flow after observing all priority rules as described previously. The key outcomes are described below.

- For all the cases modeled with only midblock (M) full-access (FA) driveways, the TWLTL merging delay was at LOS B for all cases except M16-FA at high volume with 200 vphpd and M24-FA where the delay increased to LOS C (figure 6.42).
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, for all low and medium mainline volumes and for high mainline volume at low midblock density (8 driveways), the LOS was A. The LOS was B at 50 vphpd at high mainline volume with 16 midblock driveways, and C at all remaining cases (figure 6.43).
- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, the LOS was A for all cases except 100-150 vphpd and 50-100 vphpd for 16 and 24 midblock driveways respectively with high mainline volume where the LOS was C (figure 6.44).
- The merging delays in TWLTL are not excessively high even at high mainline and high driveway volume combination cases.

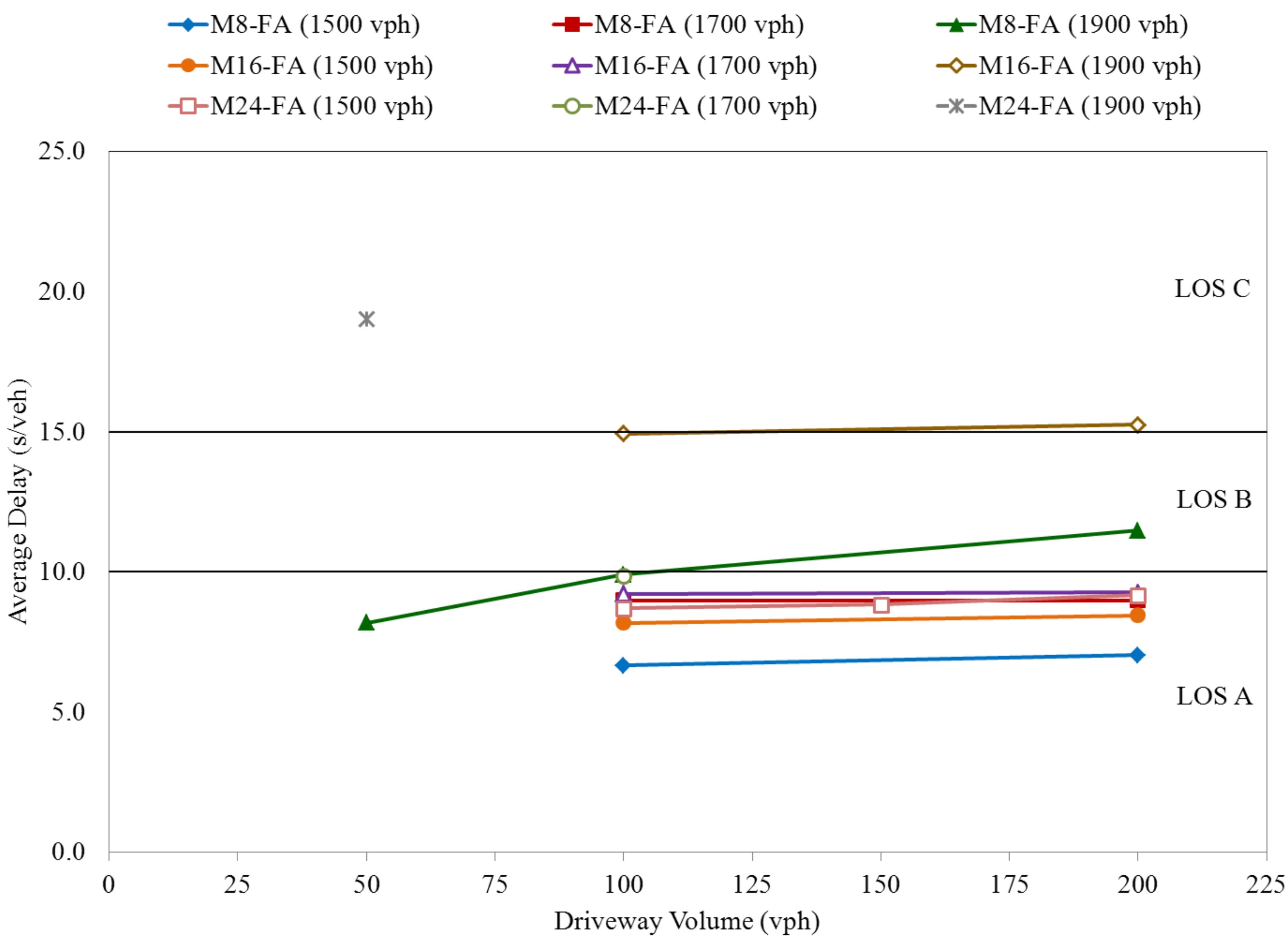

Figure 6.42 Average Delay for All Merging from TWLTL Movements for Cases M8-FA, M16-FA, and M24-FA

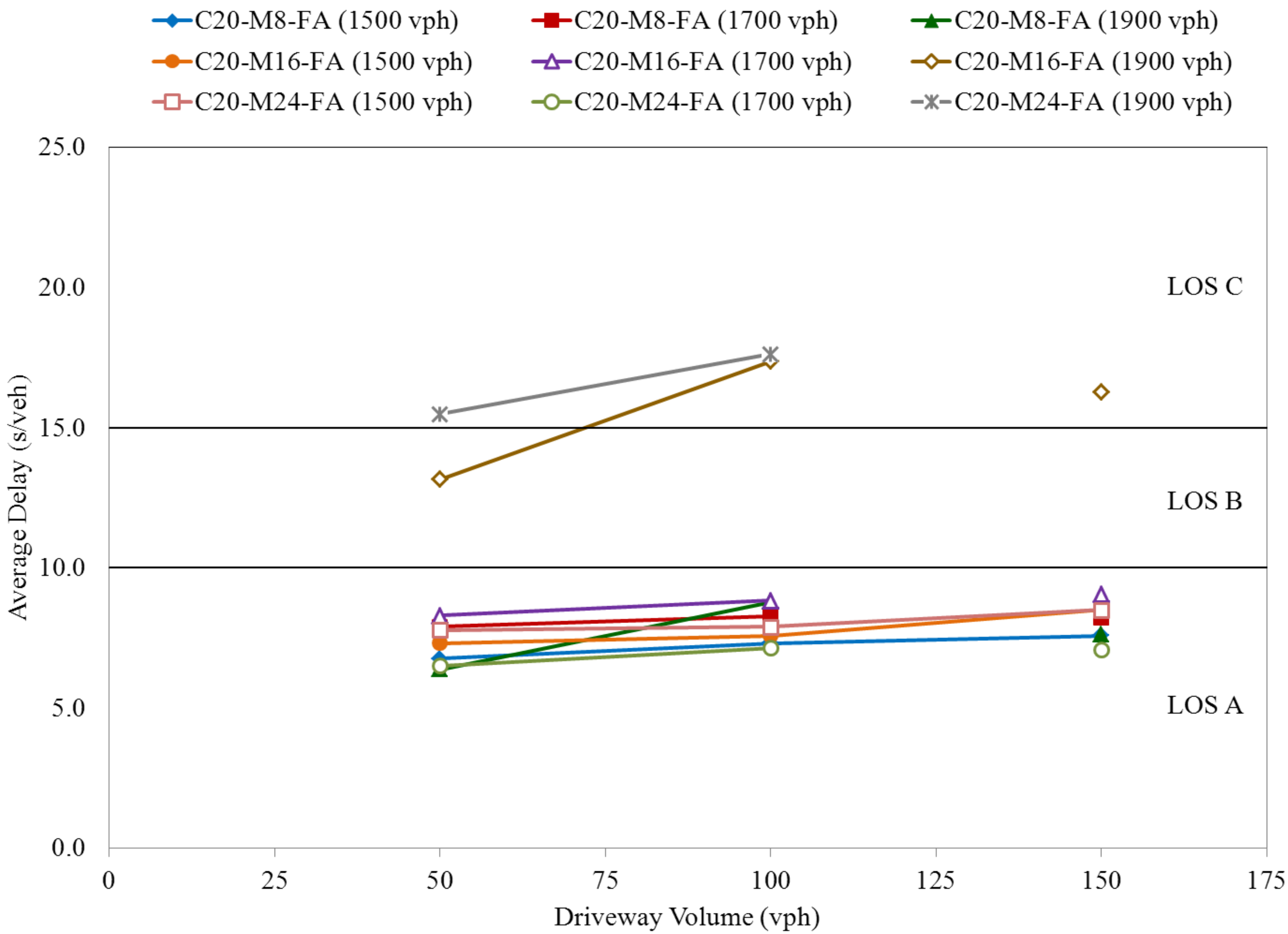

Figure 6.43 Average Delay for All Merging from TWLTL Movements for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

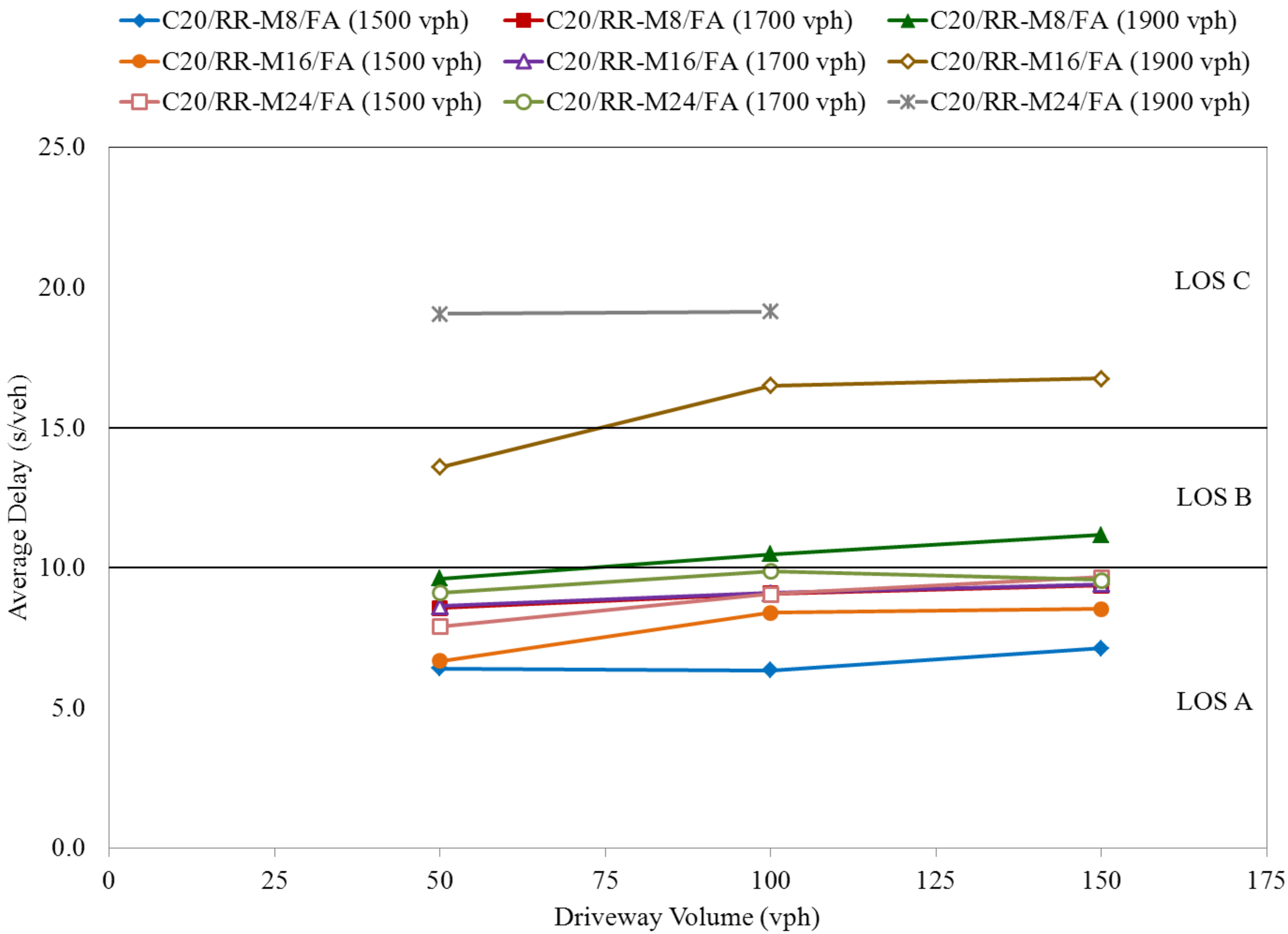

Figure 6.44 Average Delay for All Merging from TWLTL Movements for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.7 Comparison of Average Delays for All TWLTL-related Movements

Figures 6.45 to 6.47 present the average delay (s/veh) for all TWLTL-related driveway movements (left-in and merging) for all applicable cases. The main points are as follows.

- For case C20-FA (20 corner full-access driveways), the overall TWLTL delay is essentially the same as left-in delay.
- For all the cases modeled with only midblock (M) full-access (FA) driveways, the overall TWLTL delay is at LOS A for low mainline volume, LOS B for medium mainline volume, and LOS C or D for high mainline volume (figure 6.45).
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, the overall TWLTL delay is at LOS A for low mainline volume, LOS B for medium mainline volume, and LOS C for high mainline volume (figure 6.46).
- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, the overall TWLTL delay is at LOS A for low mainline volume, LOS B for medium mainline volume, and LOS C or D for high mainline volume (figure 6.47).

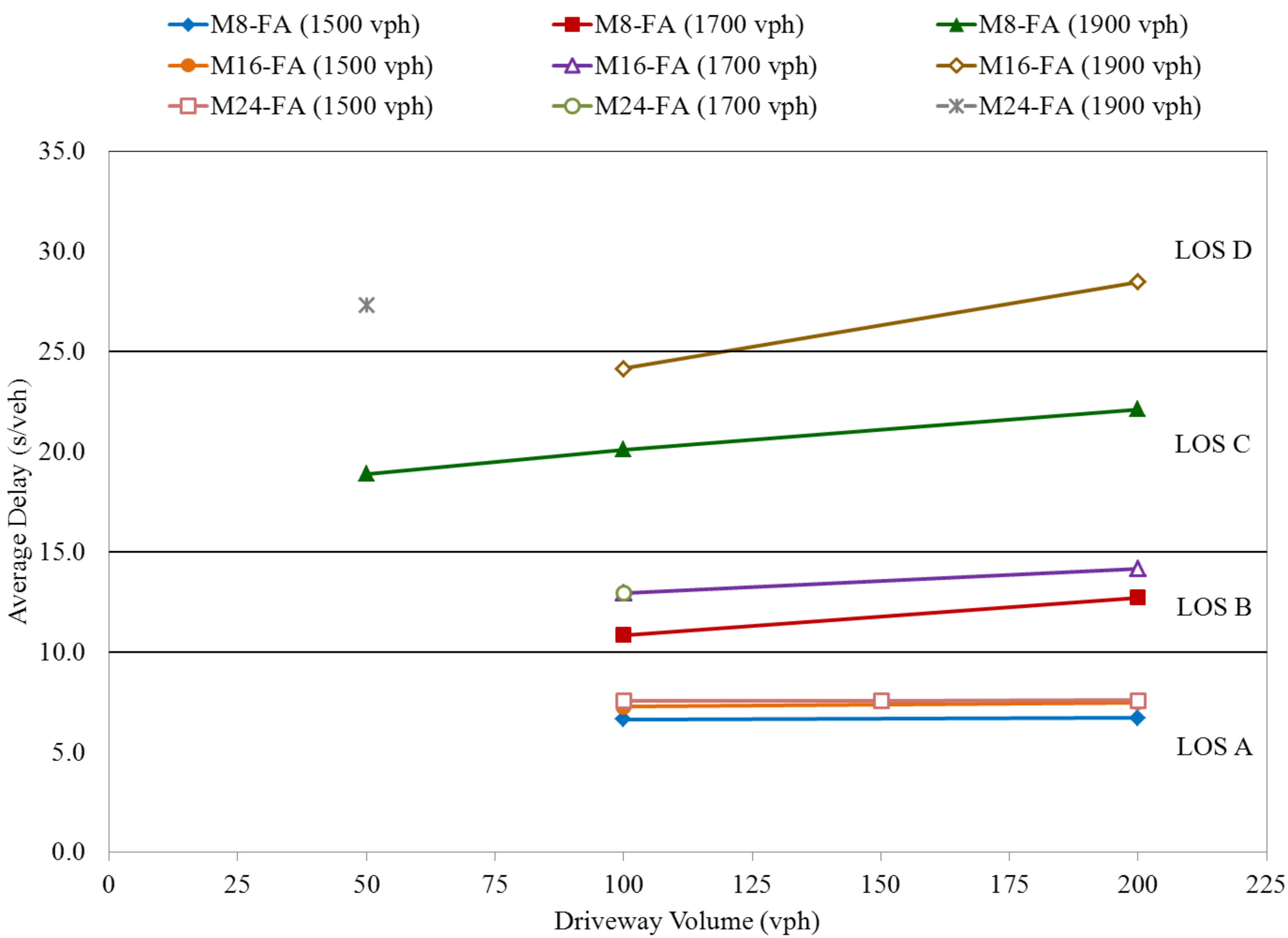

Figure 6.45 Average Delay for All TWLTL Movements for Cases M8-FA, M16-FA, and M24-FA

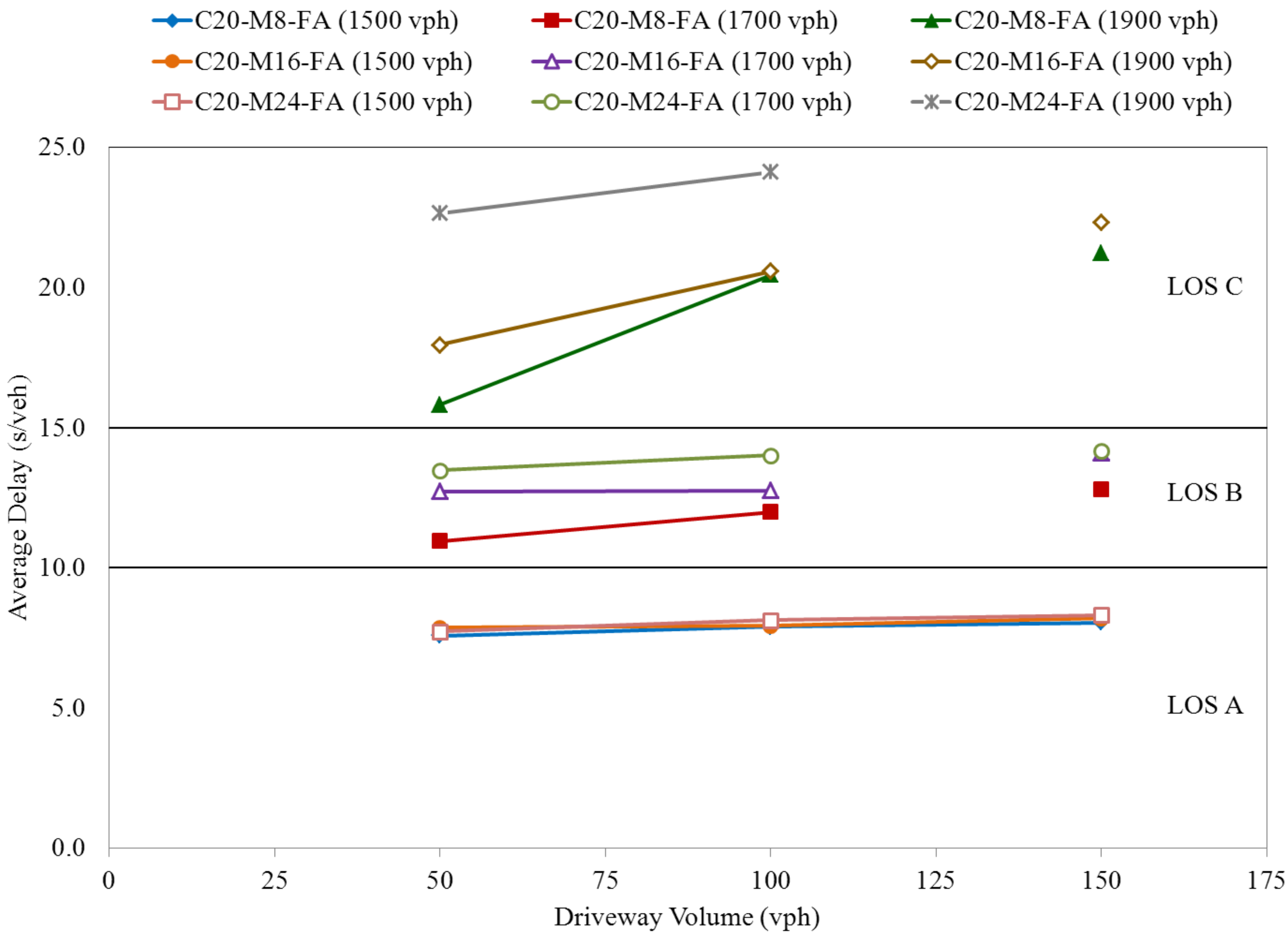

Figure 6.46 Average Delay for All TWLTL Movements for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

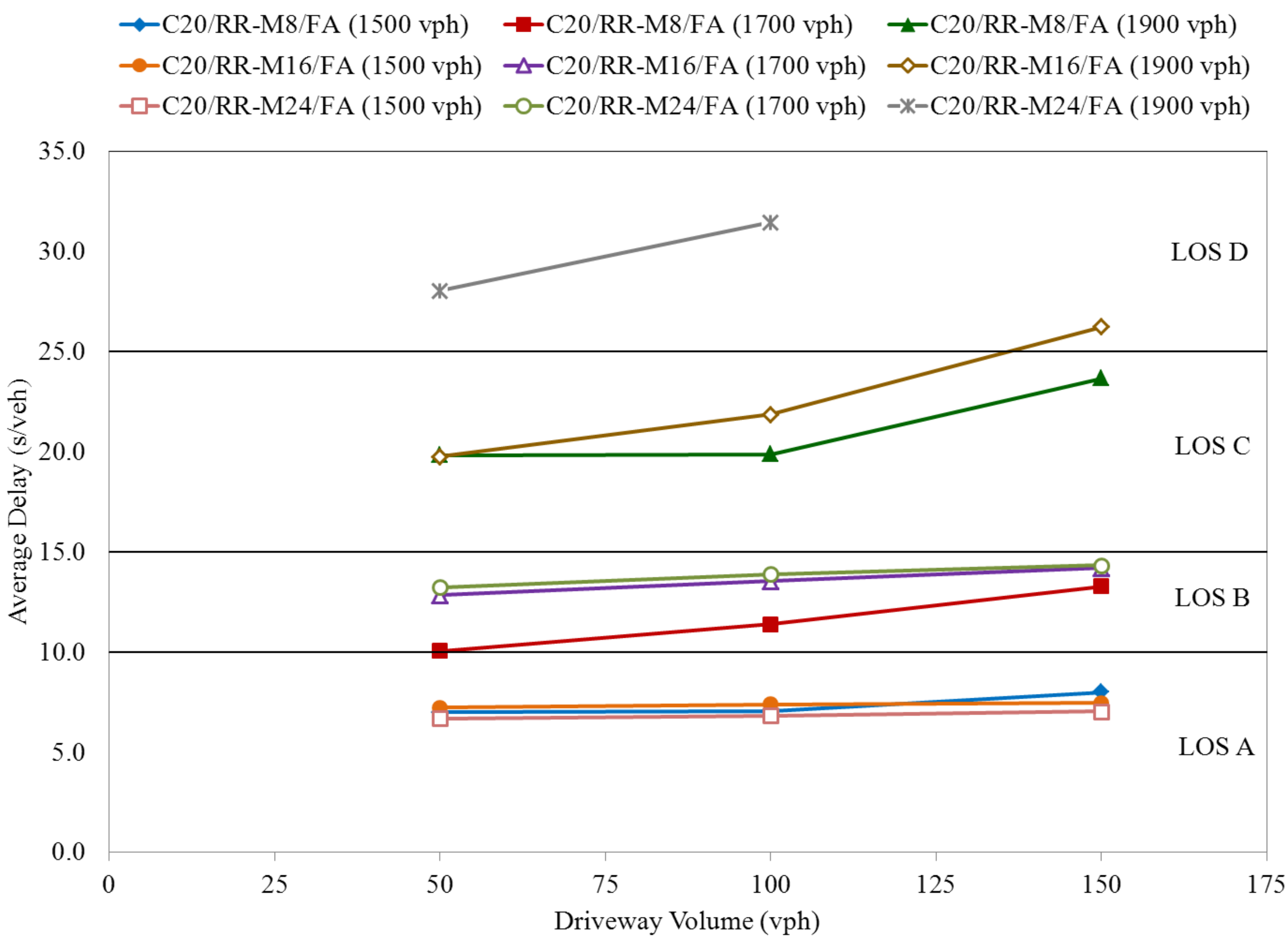

Figure 6.47 Average Delay for All TWLTL Movements for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.8 Comparison of Average Delays for All Approach-side Corner Driveways

Figures 6.48 to 6.51 present the average delay (s/veh) for all corner driveways located on the approach side of signalized intersections. For all approach side driveways, the delays shown are only for outbound traffic since left-in was not allowed. The key outcomes of this set of results are as follows.

- For case C20-FA (20 corner full-access driveways), the approach-side delay shown in figure 6.48 indicates LOS E or worse for full-access cases at medium and high mainline volumes across all driveway volumes, and also for right-in/out (RR) at high mainline and high driveway volume combination. For all other cases, the LOS is shown to be D or better.
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, the delays for approach-side corner driveways are at LOS C for low mainline volume, and at LOS F for medium and high mainline volumes across all driveway volumes (figure 6.49).
- For cases with both corner (C) and midblock (M) right-in/out (RR) driveways, the delays for approach-side corner driveways (right-out only) are at LOS C or better at low and medium mainline volumes and also for high mainline volume at 50 vphpd, and at LOS D or worse for the remaining high mainline volumes (figure 6.50).
- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, the delays for approach-side corner driveways (right-out only) are at LOS A for low mainline volume, at LOS B to C for medium mainline volume, and at LOS D or worse for high mainline volumes (figure 6.51).

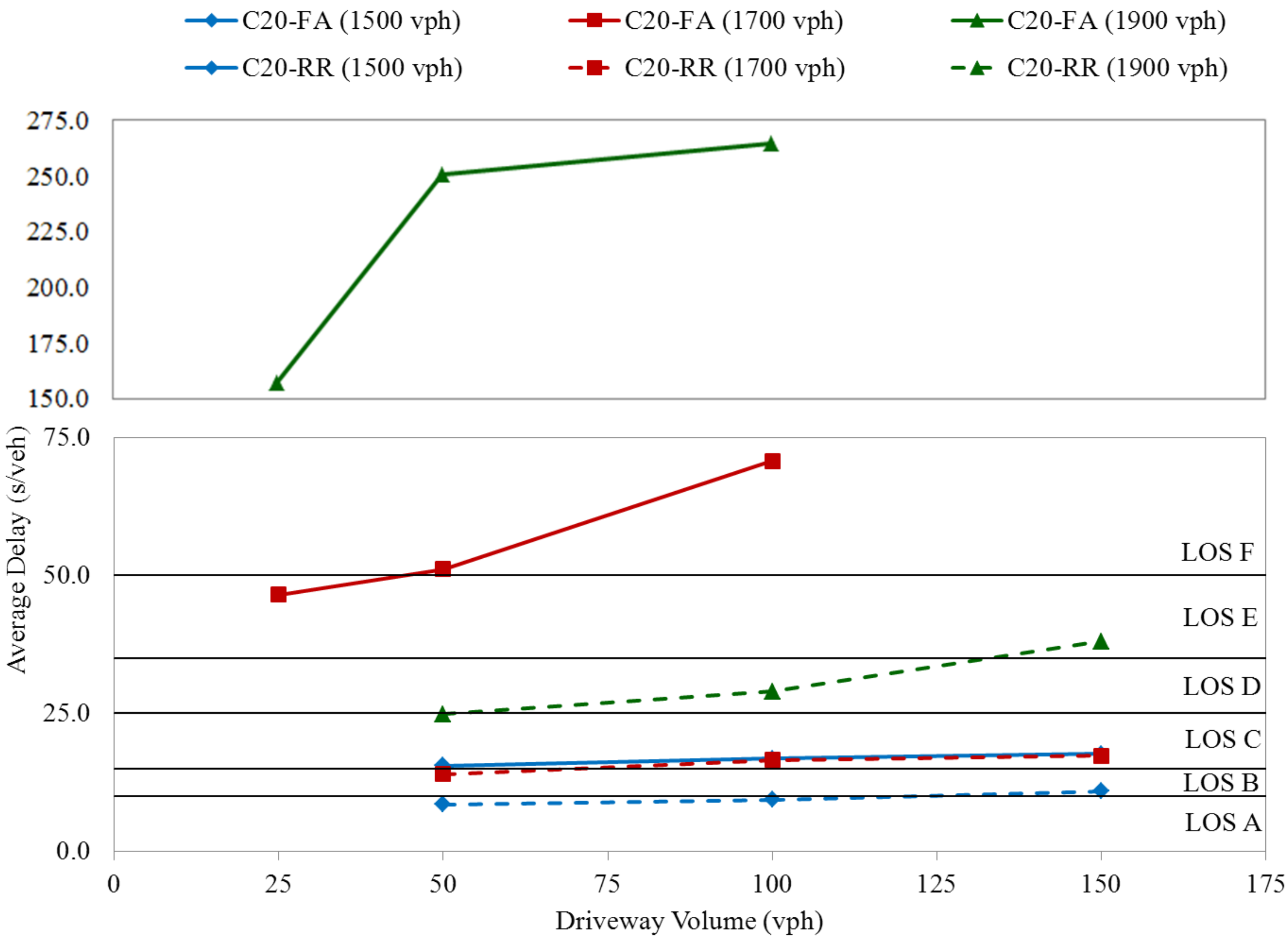

Figure 6.48 Average Delay for All Approach-side Driveways for Cases C20-FA and C20-RR

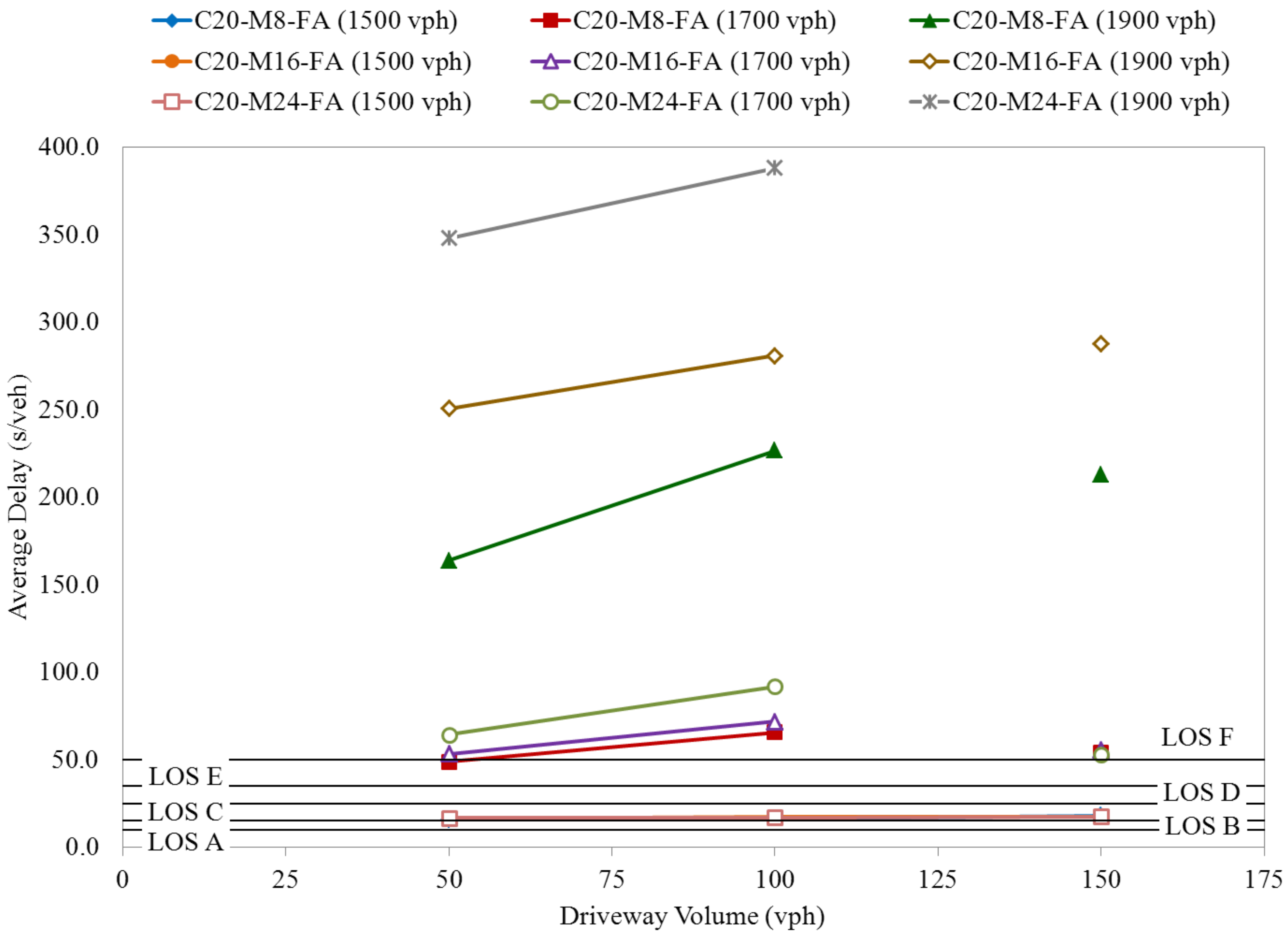

Figure 6.49 Average Delay for All Approach-side Driveways for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

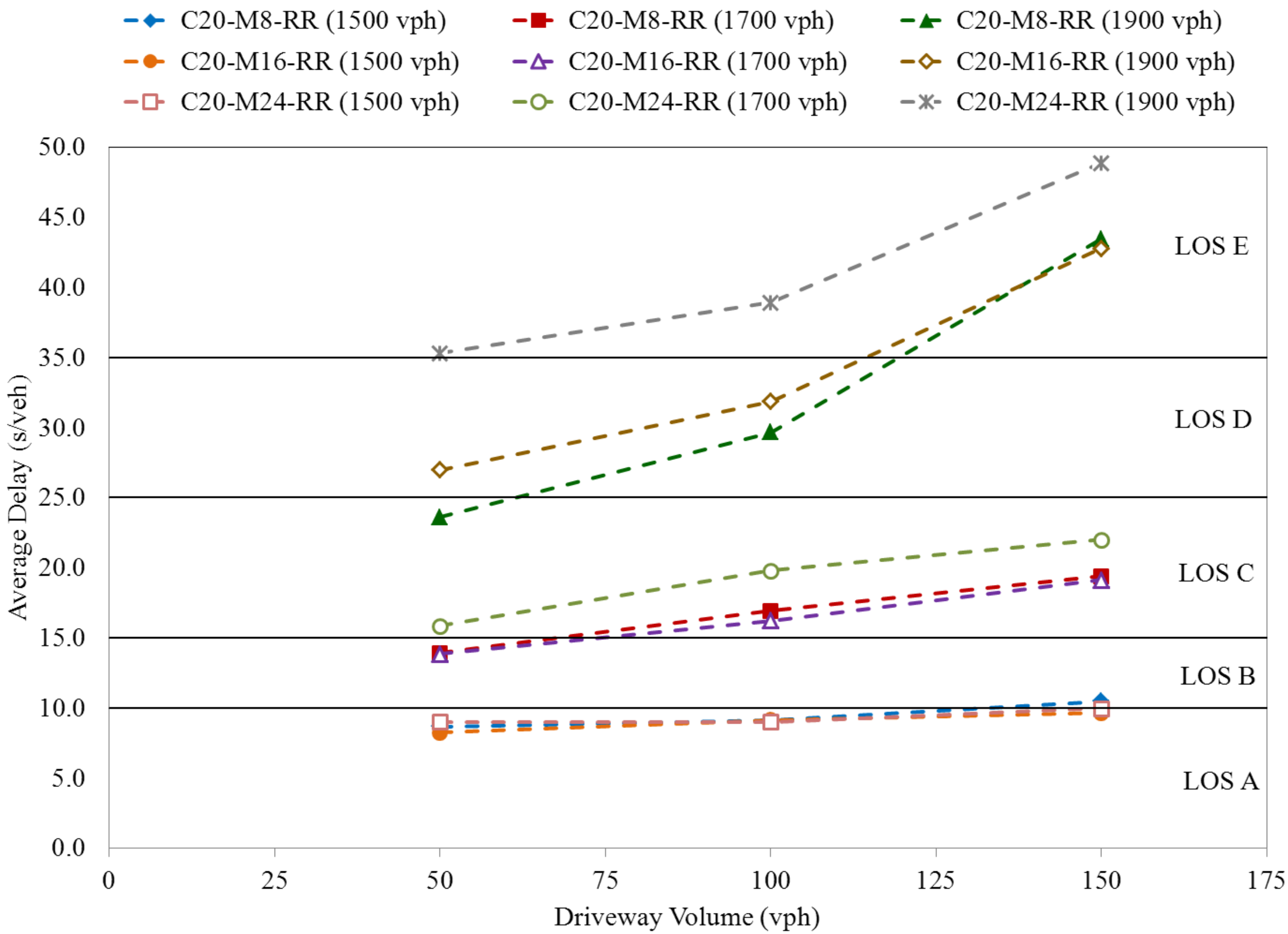

Figure 6.50 Average Delay for All Approach-side Driveways for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

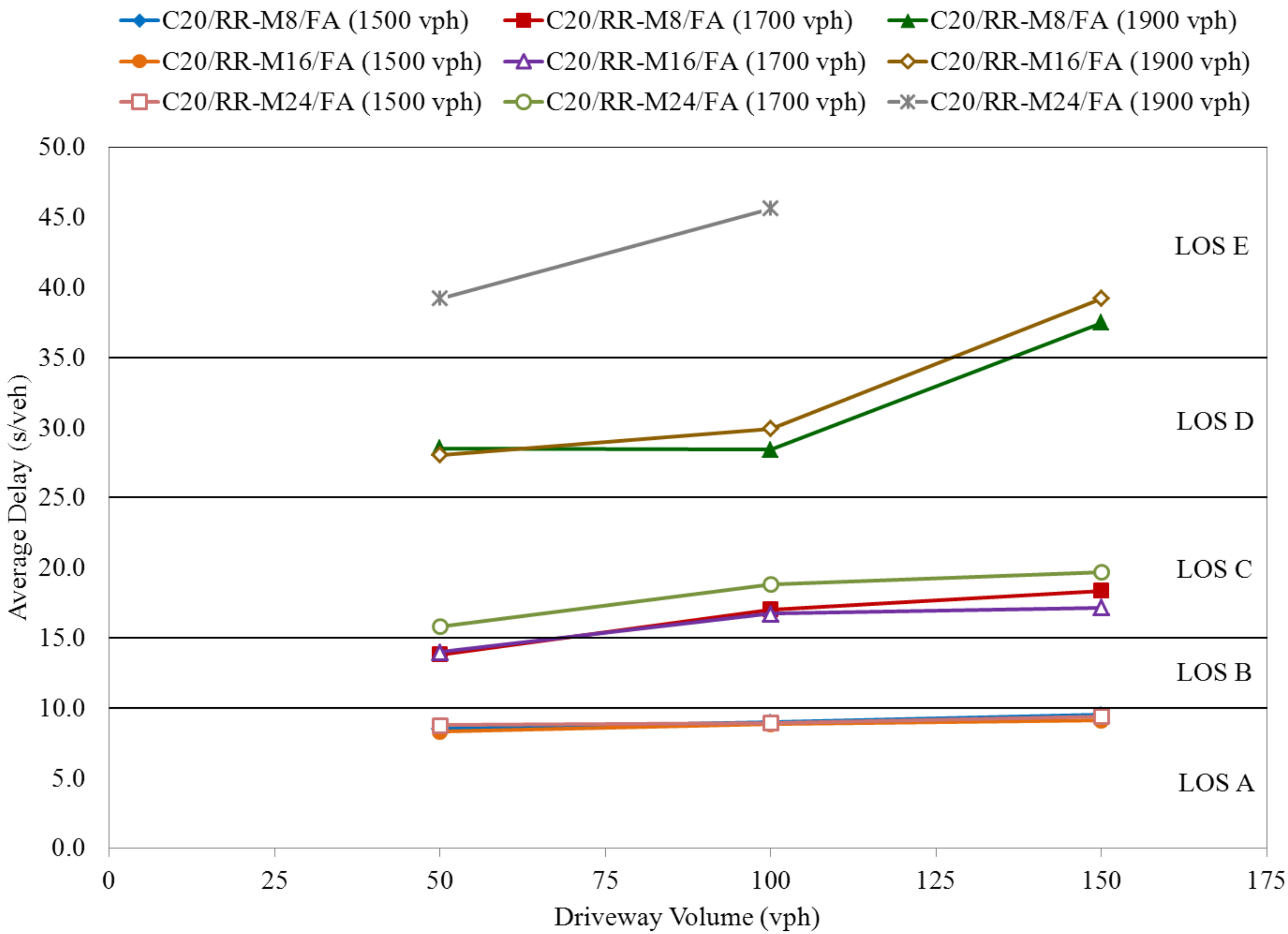

Figure 6.51 Average Delay for All Approach-side Driveways for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

6.4.9 Comparison of Average Delays for All Departure-side Corner Driveways

Figures 6.52 to 6.55 present the average delay (s/veh) for all corner driveways located on the departure side of signalized intersections. The main observations are as follows.

- For case C20-FA (20 corner full-access driveways), the departure-side delay shown in figure 6.52 indicates LOS C or better for all cases except high mainline volume cases where LOS is E or worse. The corresponding approach side delays were higher across all cases.
- For cases with both corner (C) and midblock (M) full-access (FA) driveways, delays for the departure-side corner driveways is at LOS B at low mainline volume, at LOS C or D for medium mainline volume, and at LOS E or worse for high mainline volume (figure 6.53). The approach side delays for corresponding cases were consistently higher.
- For cases with both corner (C) and midblock (M) right-in/out (RR) driveways, the departure-side delays (right-out only) for all cases across all volume and density combinations are at LOS A (figure 6.54). The corresponding approach side delays range from LOS A to LOS E.
- For cases with corner (C) right-in/out (RR) and midblock (M) full-access (FA) driveways, delays for the departure-side corner driveways (right-out only) are at LOS A for all cases except at 100 vphpd for high mainline volume and high midblock density, the LOS is at C (figure 6.55). Delays for corresponding approach side driveways were much higher.
- Overall from the evaluation of driveway-level data, the variation between driveway volumes was only significant in high mainline volume cases.

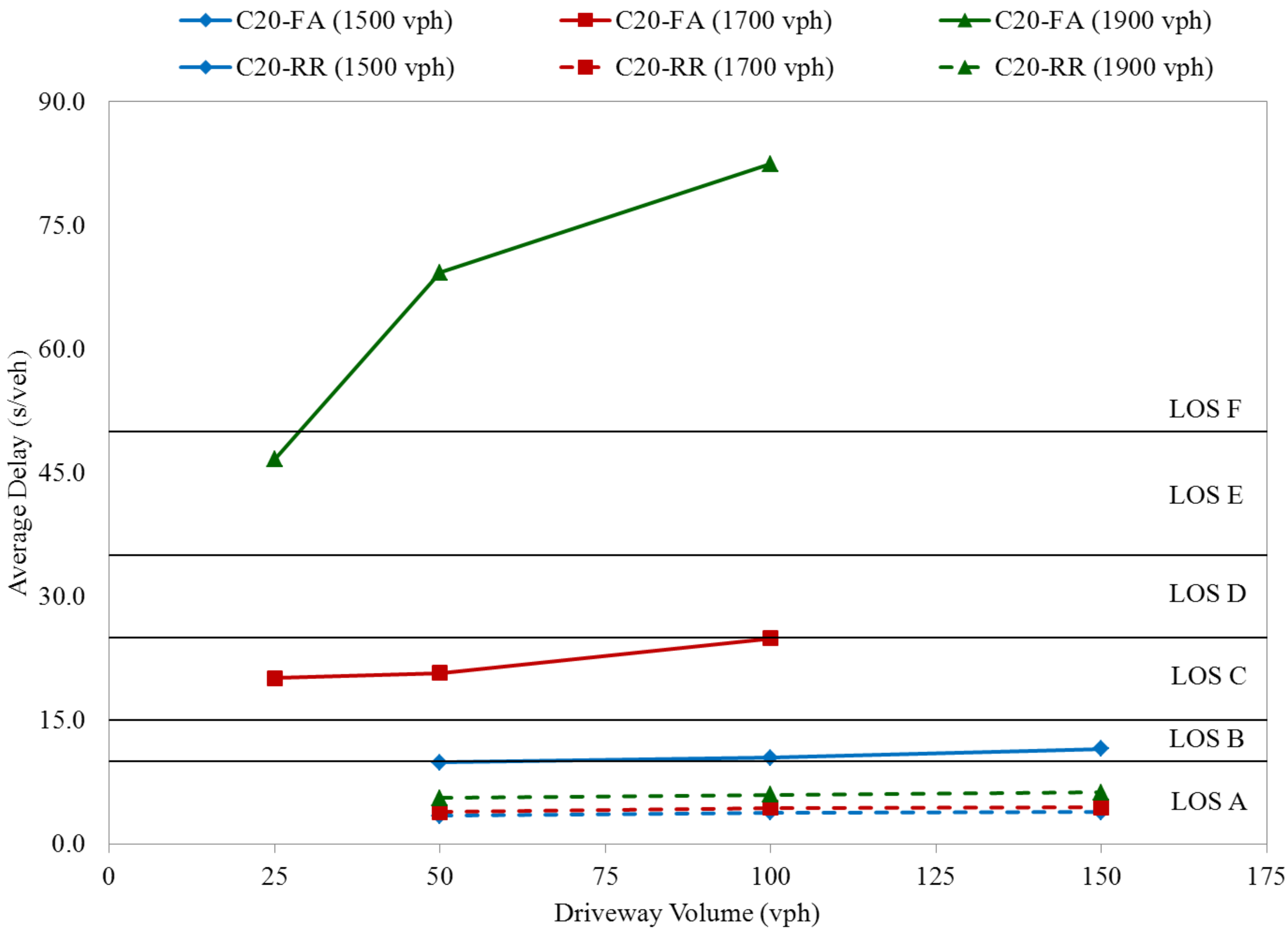

Figure 6.52 Average Delay for All Departure-side Driveways for Cases C20-FA and C20-RR

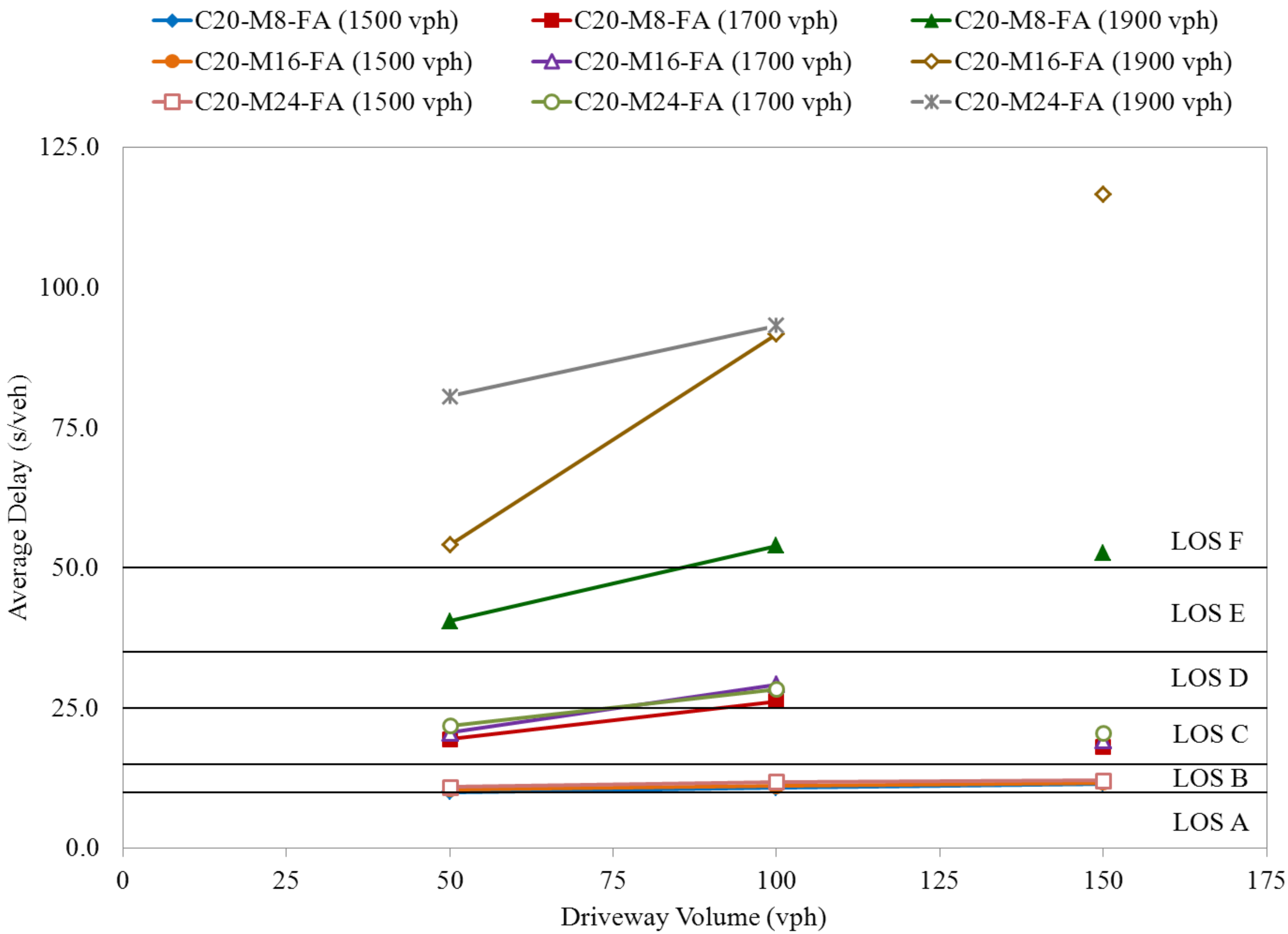

Figure 6.53 Average Delay for All Departure-side Driveways for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

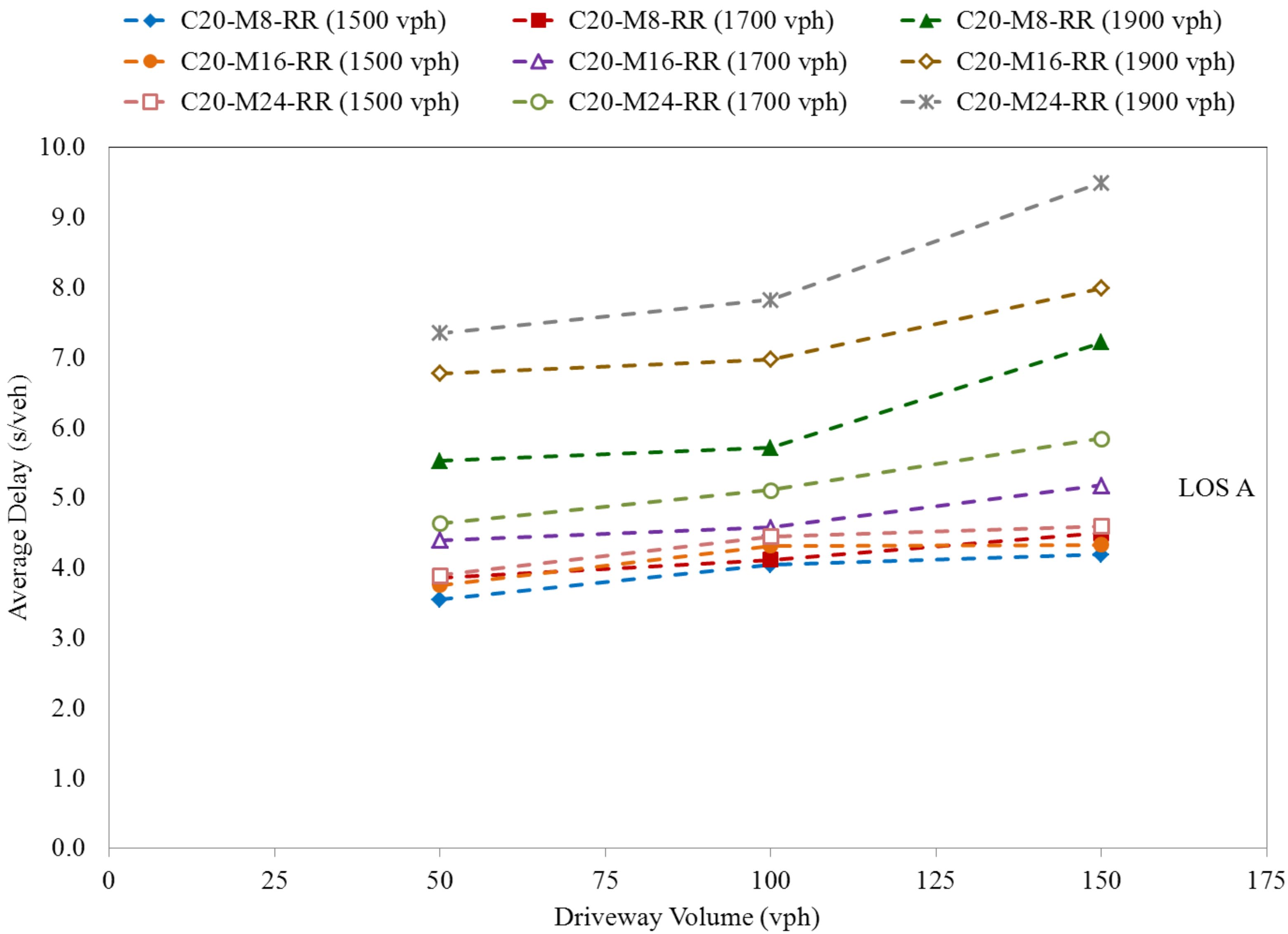

Figure 6.54 Average Delay for All Departure-side Driveways for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

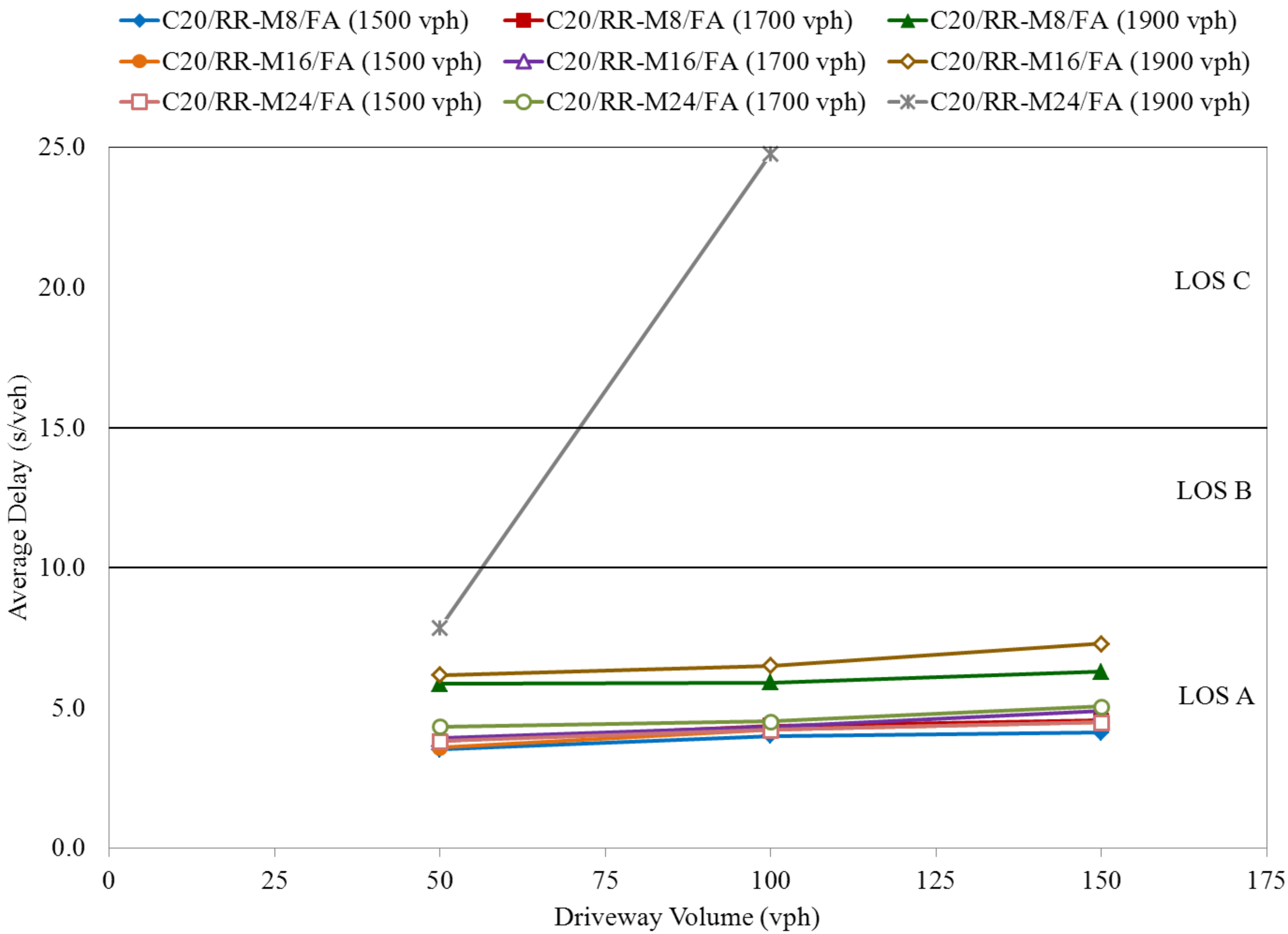

Figure 6.55 Average Delay for All Departure-side Driveways for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

A comprehensive evaluation and quantification of access management alternatives using theoretical models was presented. A summary of the overarching conclusions from this research and considerations for use by practitioners is presented in the next chapter, along with recommendations for further expansion of potentially infinite theoretical scenarios.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Systematic control of location and spacing of driveways on arterial roads is a principal component of access management. The purpose of this research was to quantify the operational impacts of varying access location, spacing, driveway volume, and through traffic volume on 5-lane urban arterials with two-way left-turn lanes (TWLTL). A comprehensive operational evaluation using micro-simulation was performed to provide guidelines for transportation engineers and planners on the impacts of access placement and restrictions.

In terms of the location, spacing, restriction, and volume variables for access management, there is a potentially infinite number of combinations that can be studied in a simulation environment. This research is addressed to these operational issues using a 1-mile corridor with five equally-spaced and optimized signals with corner and midblock driveway density varying from zero to 44. The driveway volumes were modeled in the range of 25 to 200 vph, and the mainline volumes were modeled between 1500 and 1900 vph per direction. Full-access and right-in/out turning restrictions were also added to create 136 total theoretical models.

Theoretical models were developed using VISSIM simulation software and based on field data, especially for the modeling and calibration of the traffic movements utilizing shared space in a TWLTL. It was found that using continuous overlapping links in combination with ‘priority rules’ are more effective in modeling TWLTL instead of individual movement-specific connectors. Given the modeling capabilities of VISSIM, the minimum driveway offset spacing (edge-to-edge) for opposing driveways that could be modeled without creating queues outside the TWLTL was found to be 85-ft with driveway volumes of up to 200 vph. The minimum corner clearance that is feasible to model in VISSIM was found to be 150-ft which was primarily limited by the minimum distance of 100-ft required for static routing decisions for full-access corner driveways. Note that these limitations are based on using 'static routes' where each development was assumed to be served by only one driveway. Also, the upper limits on minimum driveway spacing and clearance do not necessarily correspond with the maximum deterioration of traffic operations across all cases. The minimum gap acceptance data used in simulation for various driveway movements as measured in the field was: 3.1 seconds for left-out driveway movement, 3.6 seconds for left-in movement from a TWLTL, and 3.0 seconds for right-out driveway movement.

The operational evaluation was performed at three levels: corridor-wide, signalized intersections, and driveway-specific. Average delay (s/veh) was the primary MOE selected for analysis and comparison between individual models. The practical significance of difference between a set of alternatives at the corridor-level is dependent on the initial operating conditions. At the signalized intersection and for the driveways, the significance was determined based on the HCM's recommended average delay thresholds for LOS.

At the corridor-level, the simulated traffic volume per hour was increased up to 28.0% from the baseline case without any driveways. The increase in average delay ranged from 6.0% for case M8-RR (8 midblock driveways, all right-in/out) with 100 vphpd at low mainline volume to approximately 41.6% for case C20-M24-RR (20 corner and 24 midblock driveways, all right-in/out) with 150 vphpd at high mainline volume.

At the signalized intersections, the variation in average delays between cases was found to be small, with none of the intersections in any model shifting towards a better or worse LOS. However, it is emphasized that direction-specific delays do have an impact on the driveway traffic especially at corner driveways as indicated by increased out- and in-bound delays with an increase in the mainline volume for a given case.

In the evaluation of driveways, the trends in increased delays were as expected, with increasing values as the number of driveways increased especially in full-access cases. The main overarching finding was that the impact of mainline volume is much more significant on driveway operations than the impact of increased driveway density. At low mainline volumes, high access density (20 corner and 24 midblock driveways) and high driveway volume did not have a significant impact on average overall driveway delays. Also, the impact of driveway volumes is more pronounced at high mainline volumes. For low to medium mainline volumes, the increase in driveway volume did not have a significant impact on driveway delays. Given the limitation in simulation modeling as described earlier, the volumes in TWLTL (left-in/out) were only modeled up to the values that limited the TWLTL delays at LOS C even under high mainline and density combinations. Driveway volumes that resulted in excessive delays in the TWLTL such that the turning vehicles queued-up on the mainline and blocked through traffic resulted in situations (models) that the software was unable to handle in terms of processing the minimum number of vehicles in the analysis hour.

7.2 Guidelines for the Comparison of Theoretical Models

The overall purpose of this research was the quantification of the seemingly intuitive operational impacts of access management on urban arterials. In addition to the modeling of TWLTL using micro-simulation, the major contribution of this research is summarized in the form of flowcharts (and accompanying tables in appendices) that allow for cases-by-case comparison of the impacts of changing mainline volume, driveway volume, driveway location, driveway density, and driveway type on traffic operations at both the corridor and the driveway levels. Figures 7.1 through 7.9 summarize all the theoretical models that were created for this study. Within each set of models in the flowchart, reference to a table containing data for the subset of cases is also shown. These tables are provided in appendices B, C, and D.

Figures 7.1 to 7.3 include cases with low mainline volume. Figures 7.4 to 7.6 include cases with medium mainline volume, and figures 7.7 to 7.9 include cases with high mainline volume. These figures and reference tables essentially provide the guidelines for transportation analysts based on their variable of interest.

For example, to determine the impact of mainline volume from medium to high on an arterial with 16 mid-block full-access driveways at 100 vphpd, locate the cases on the flowcharts (figure 7.5 for medium, and figure 7.8 for high mainline volume), then navigate to the tables containing data referenced in these figures (tables C.6 and D.6). The data indicate that at the corridor level, the total delay increased from 184.8 hours with medium mainline volume to 232.5 hours with high mainline volume. The average driveway delay per vehicle increased from 7.2 (s/veh) to 10.9 (s/veh) or from LOS A to LOS B. From the perspective of operational guidelines, this indicates that increasing mainline volume up to 1900 vph per direction may have a significant impact on driveway-related delay; however this increase (from LOS A to B) may be considered acceptable by most engineers and planners. Similarly, comparisons can be made between any set of cases as desired. Recommendations for the use of guidelines in similar corridors are discussed in the next section.

7.3 Recommendations

There is need for a consistent set of criteria for access location and spacing for use by transportation planning agencies. In this regard, this research provides important data on the quantification of access management alternatives. However, given the possibility of modeling any number of scenarios, additional research can be done based on the modeling techniques provided in this work.

The use of guidelines is recommended albeit with caution to account for local variables that can compound the impact on traffic operations. These may include variations in minimum gap times, impact of side-street traffic, regulations on the use of TWLTL, signal optimization schemes, and so on. It is conceivable that these guidelines can be used in similar corridors, for example all cases modeled with right-in/out only driveways essentially are 4-lane roads, and the data generated may be validated from similar corridors. The tables may also provide some sense of operations at 3-lane sections with TWLTL.

In terms of modeling in VISSIM, the impact of variations in the gap acceptance time for various driveway movements may be modeled in future studies. Also the use of dynamic routes and its impact on TWLTL movements to determine the upper limits on traffic operations (at least in a simulation environment) would be important while studying the impact of frontage roads and/or developments with multiple access points.

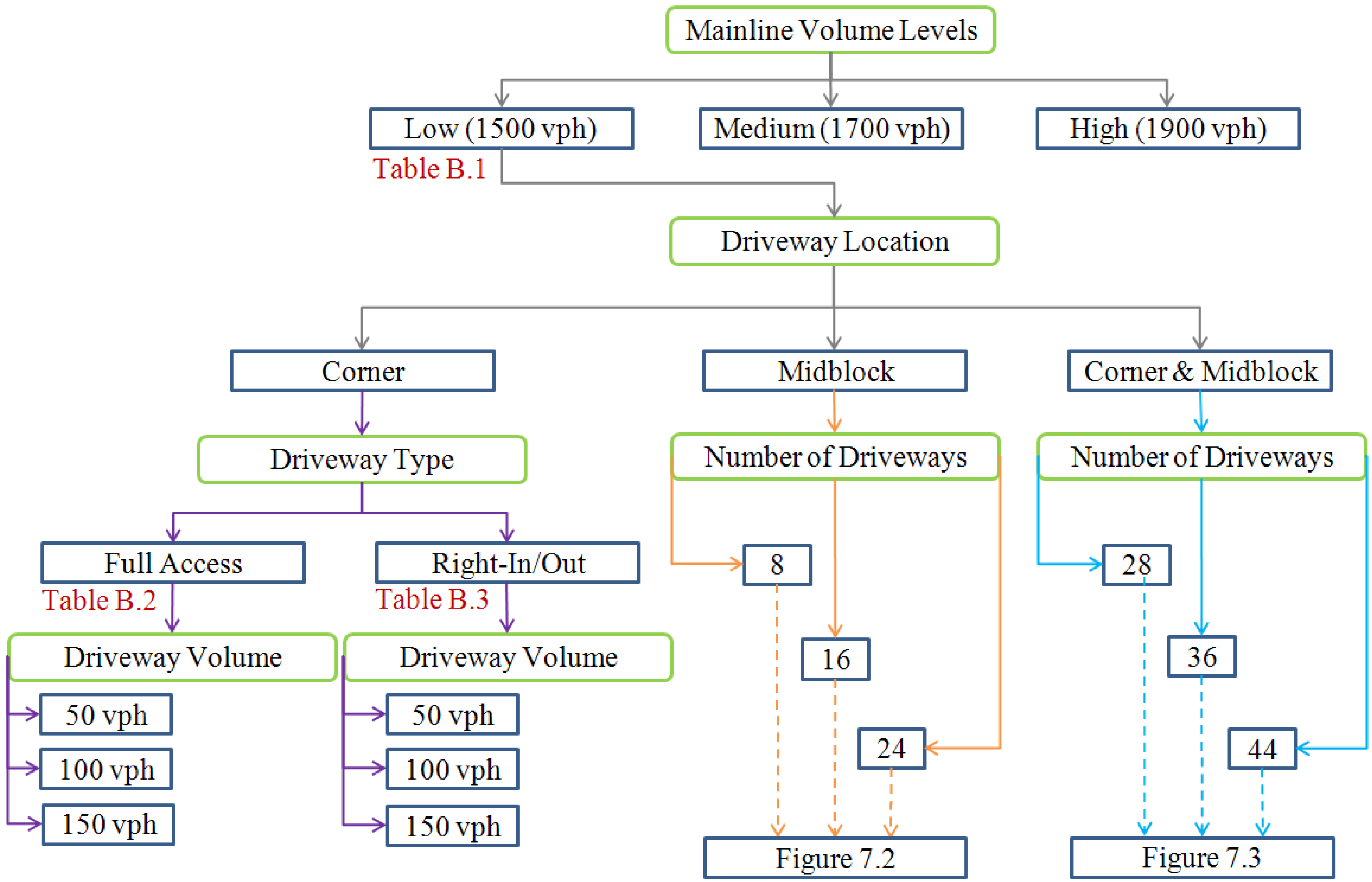

Figure 7.1 Flowchart for Low Mainline Volume and Corner Driveway Cases

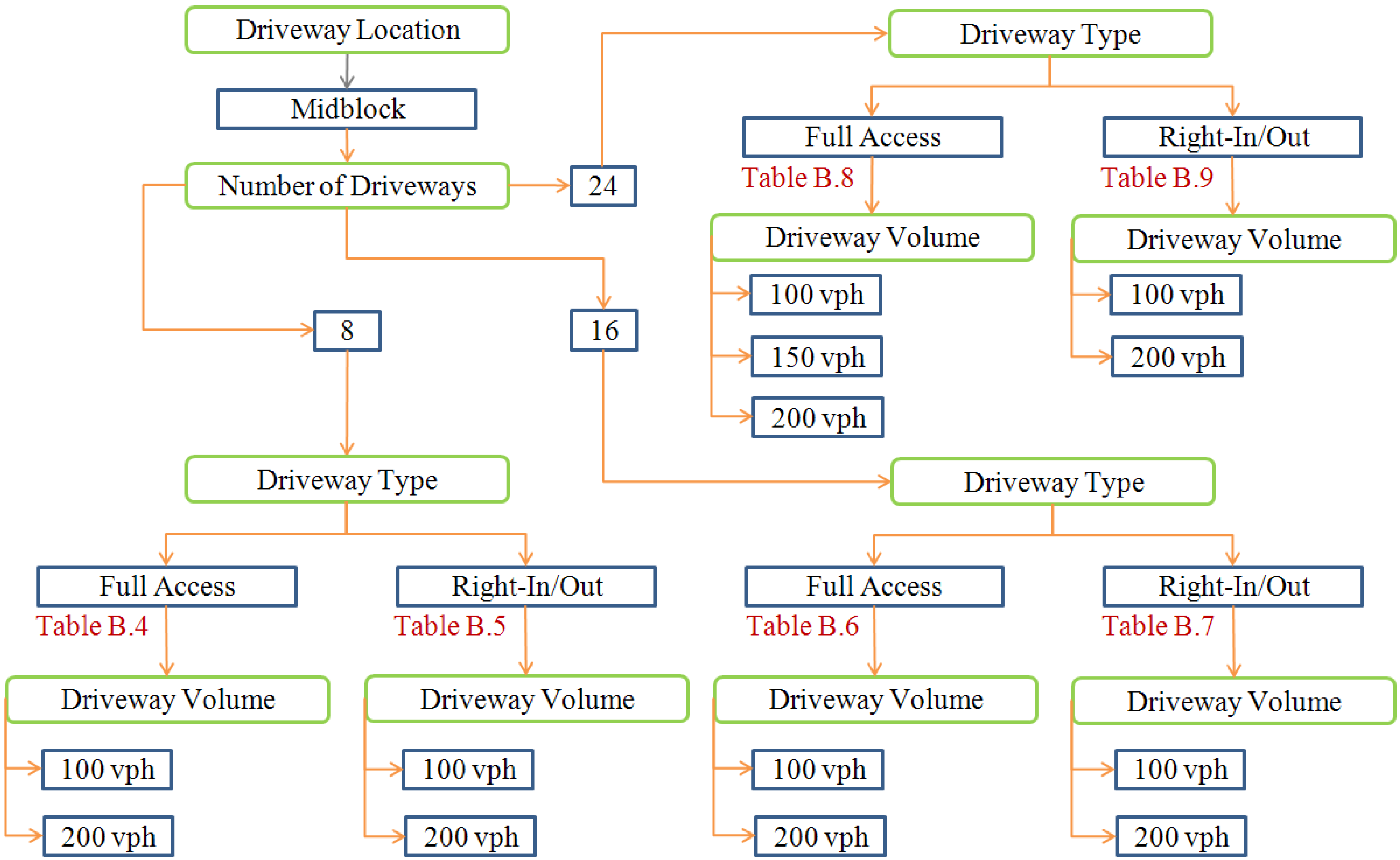

Figure 7.2 Flowchart for Low Mainline Volume and Midblock Driveway Cases

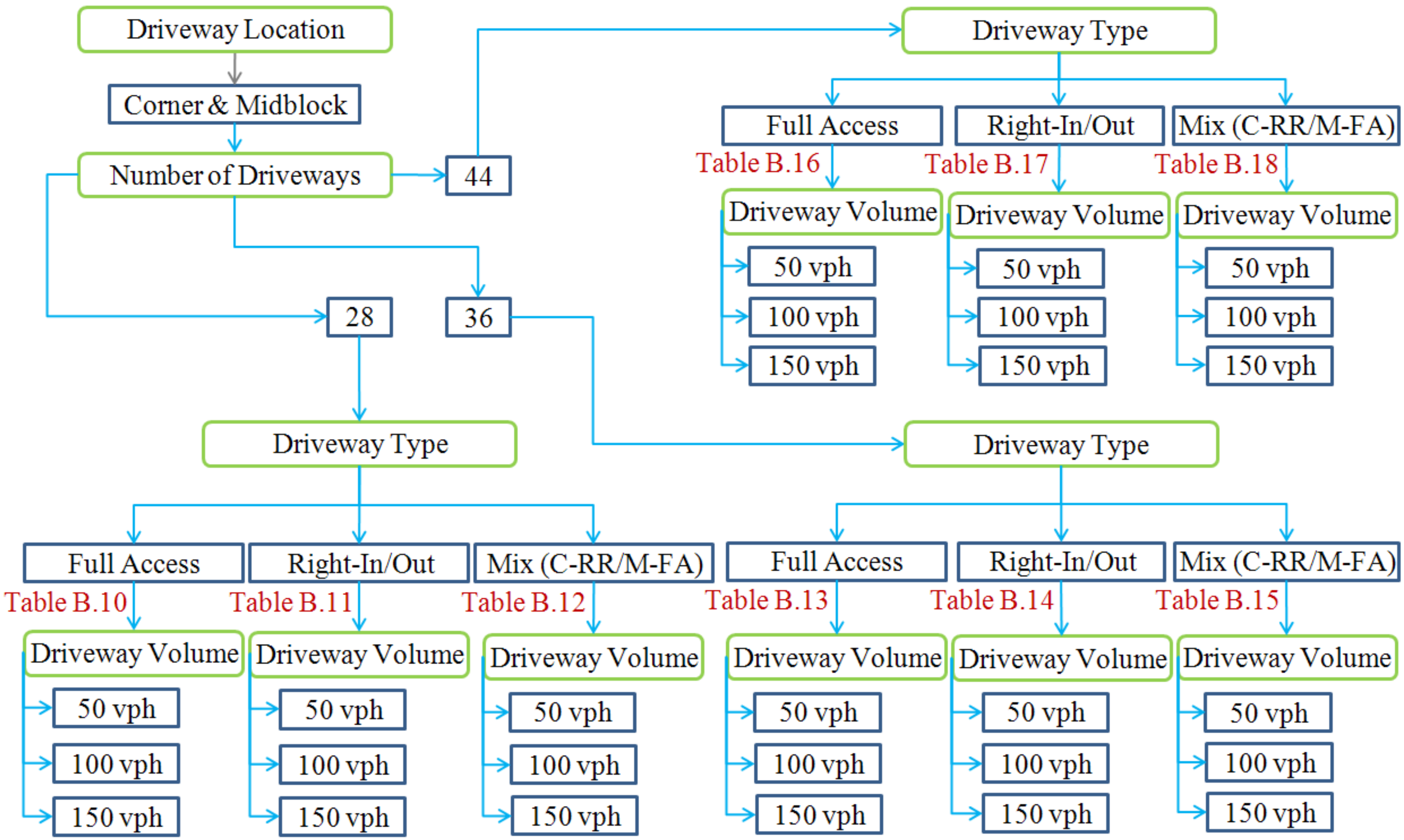

Figure 7.3 Flowchart for Low Mainline Volume and Corner- and Midblock Driveway Cases

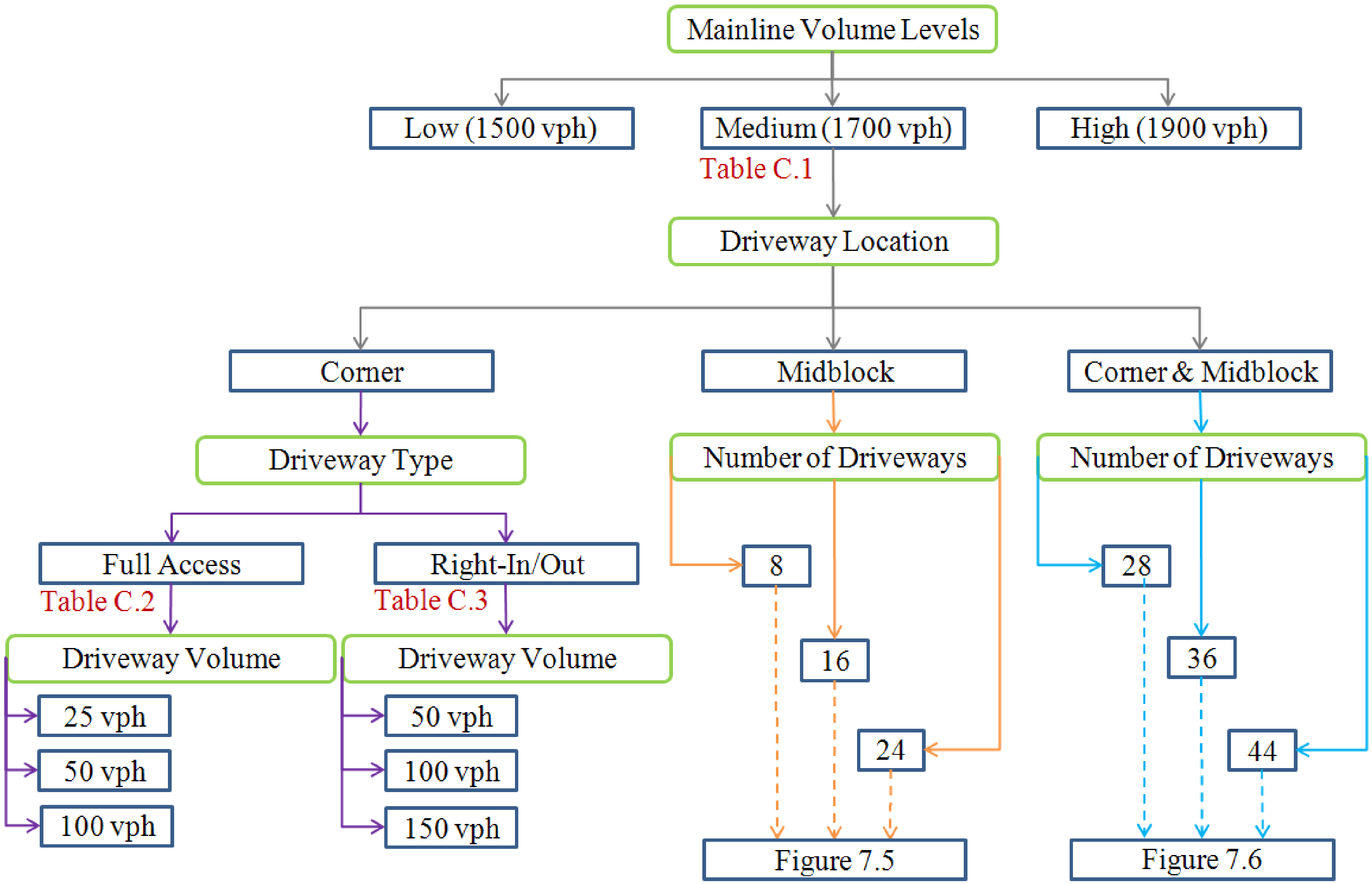

Figure 7.4 Flowchart for Medium Mainline Volume and Corner Driveway Cases

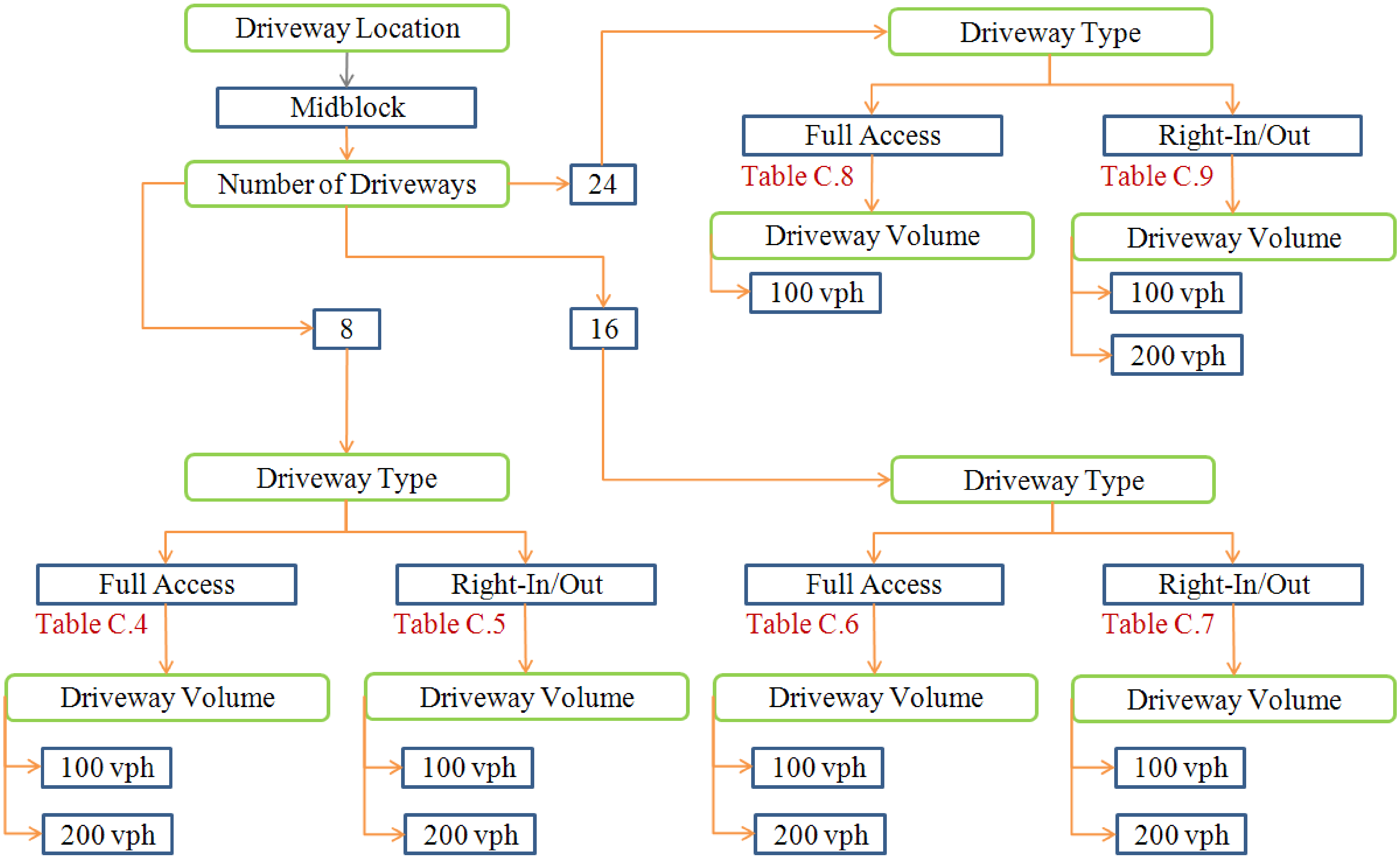

Figure 7.5 Flowchart for Medium Mainline Volume and Midblock Driveway Cases

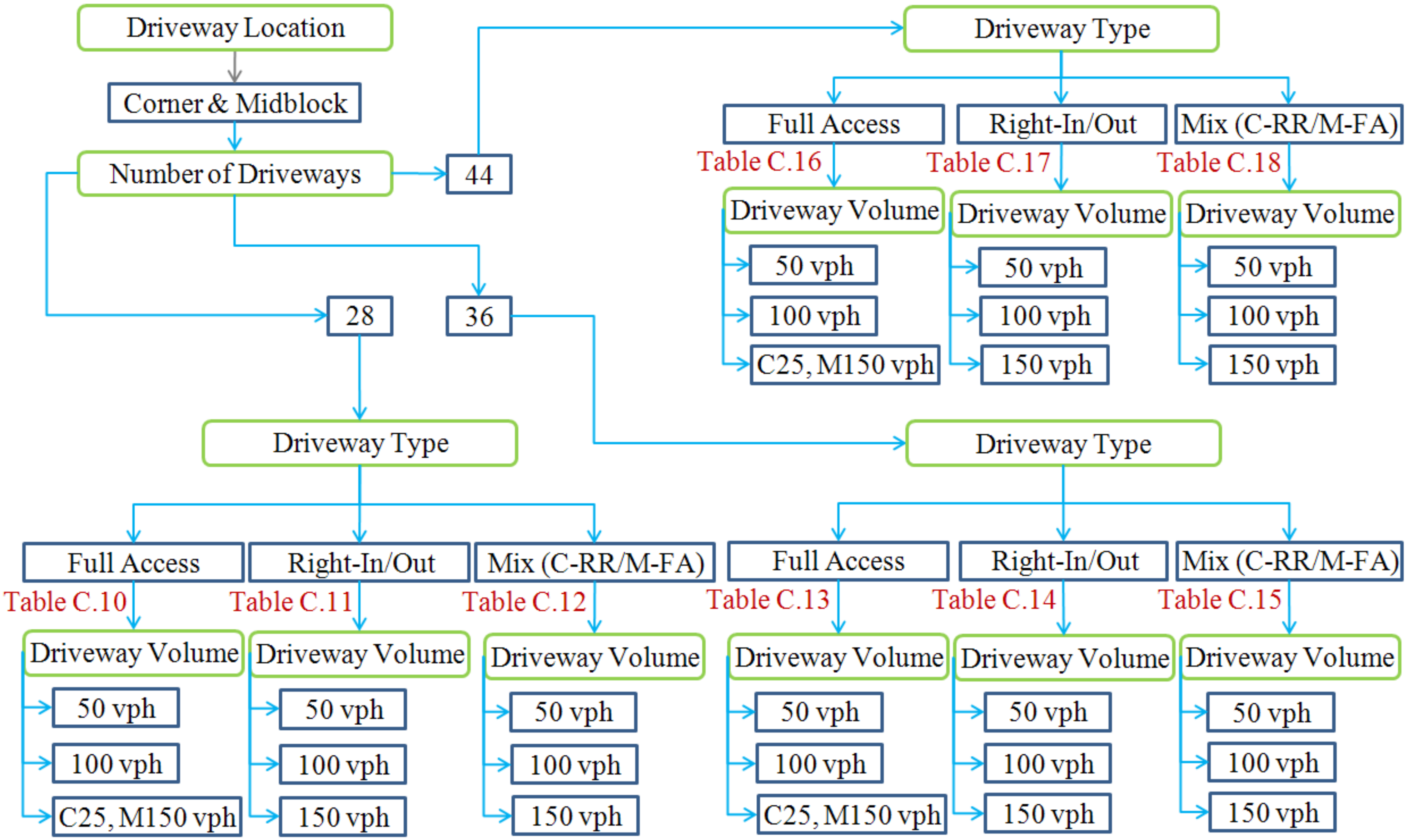

Figure 7.6 Flowchart for Medium Mainline Volume and Corner- and Midblock Driveway Cases

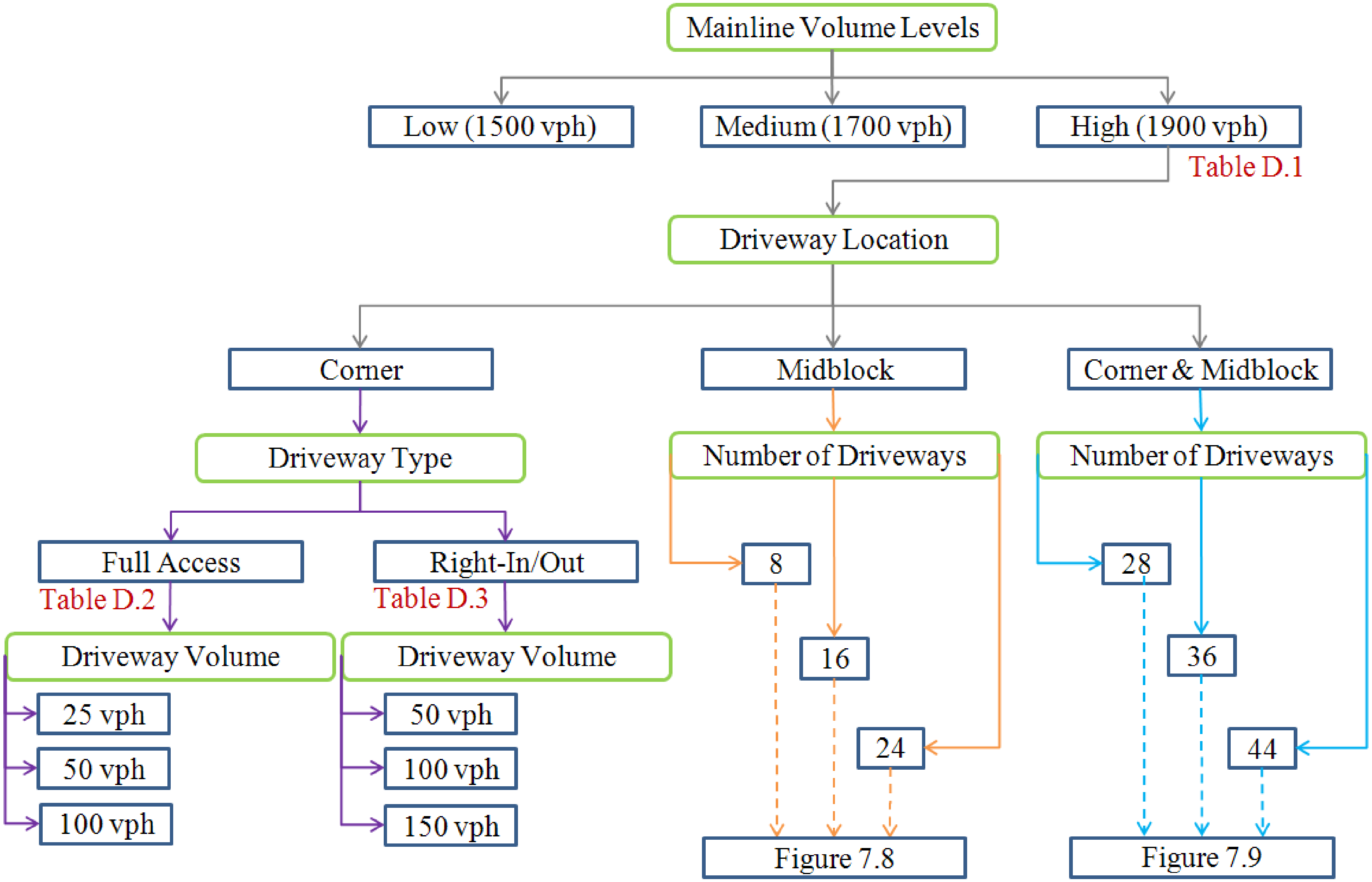

Figure 7.7 Flowchart for High Mainline Volume and Corner Driveway Cases

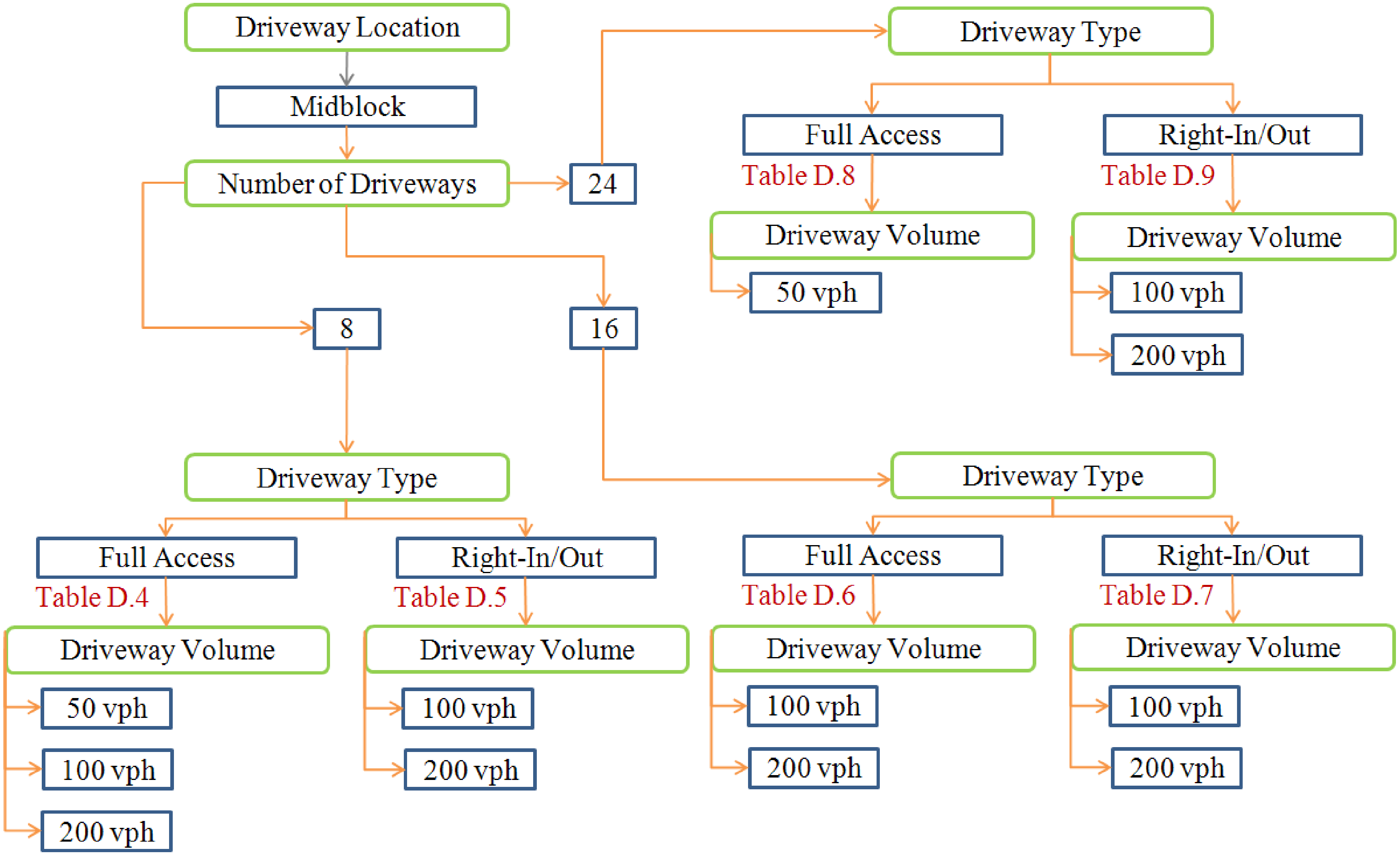

Figure 7.8 Flowchart for High Mainline Volume and Midblock Driveway Cases

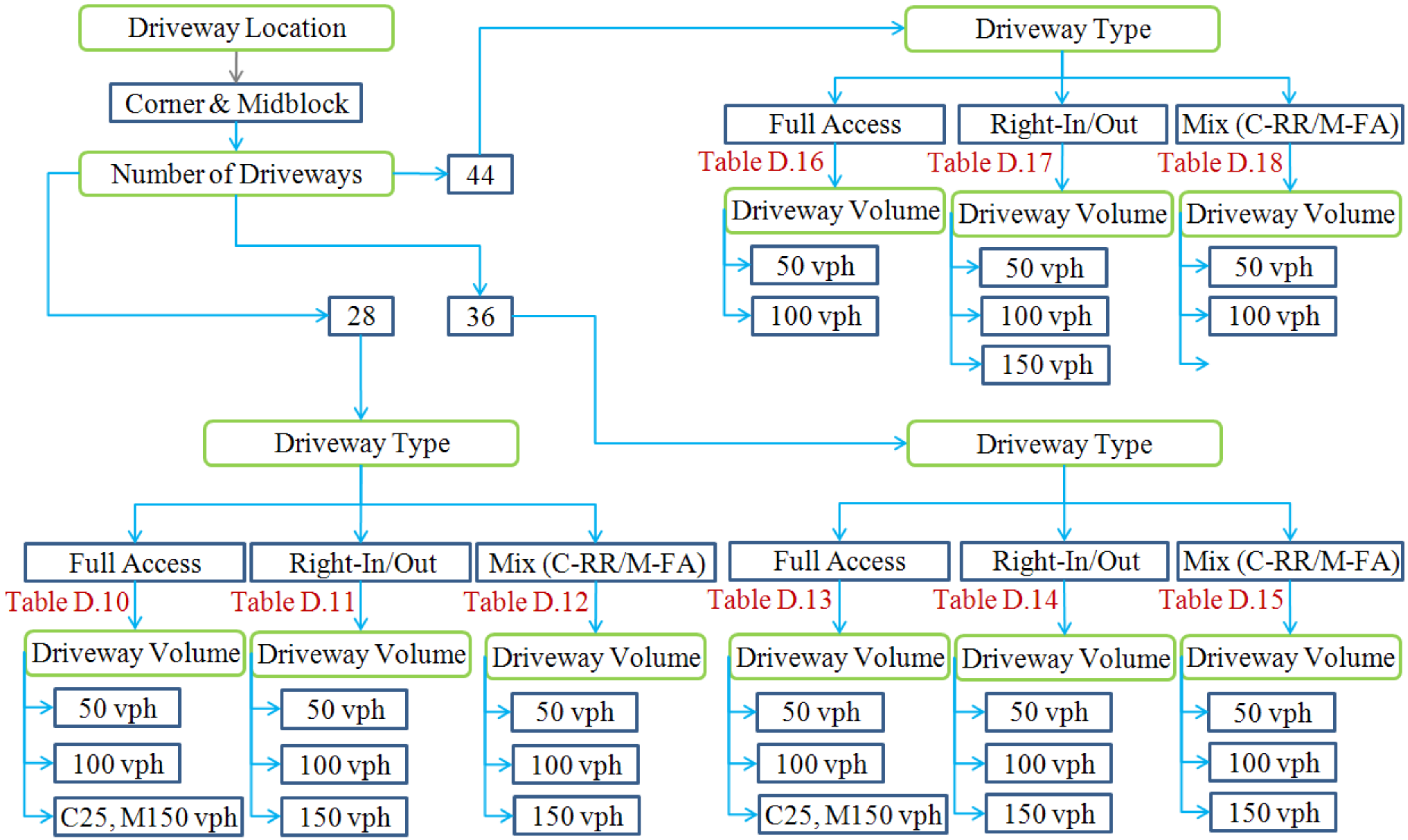

Figure 7.9 Flowchart for High Mainline Volume and Corner- and Midblock Driveway Cases

APPENDICES

APPENDIX A

Corridor-wide Evaluation Results

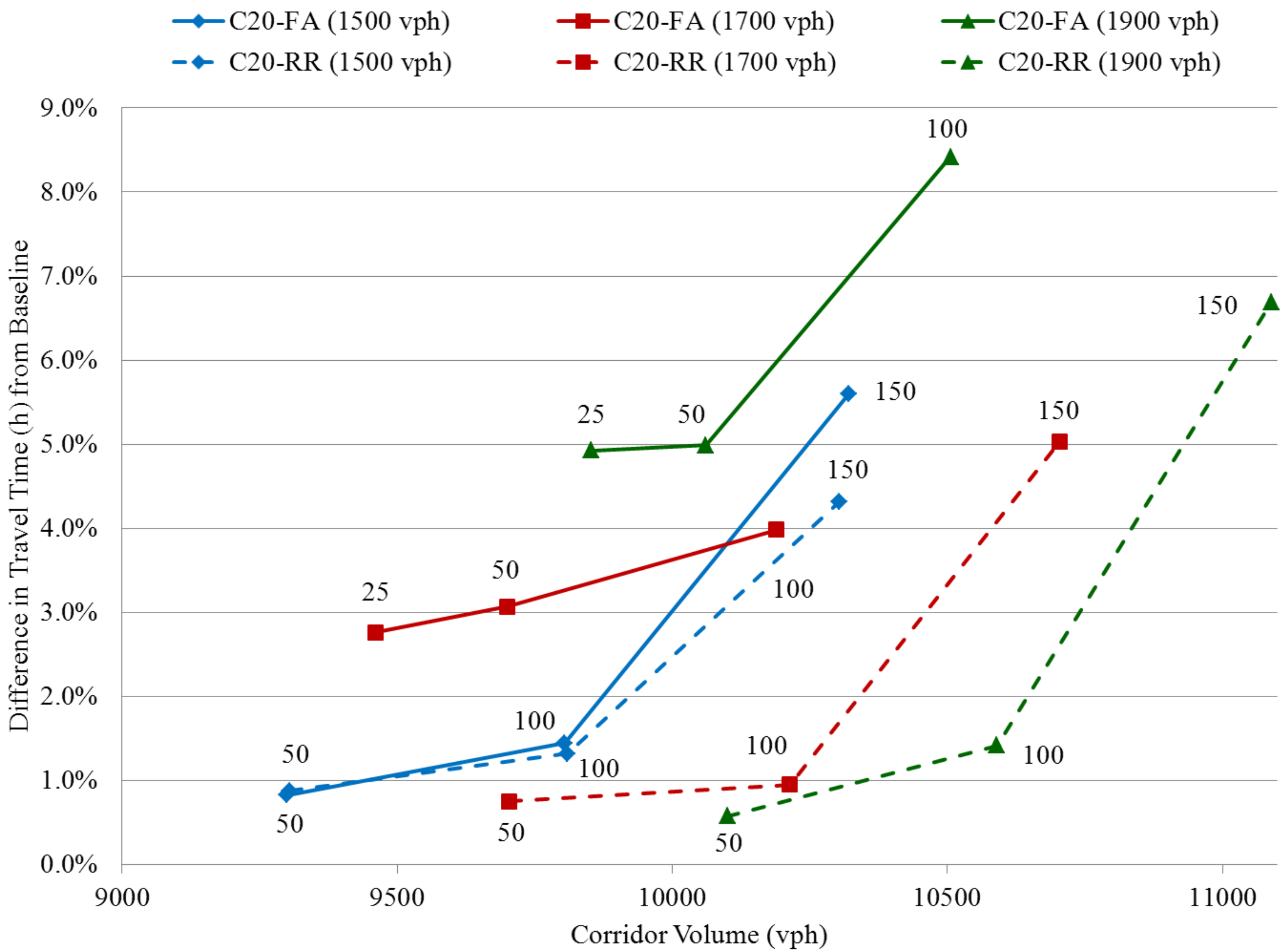

Figure A.1 Corridor-wide Difference in Travel Time for Cases C20-FA and C20-RR

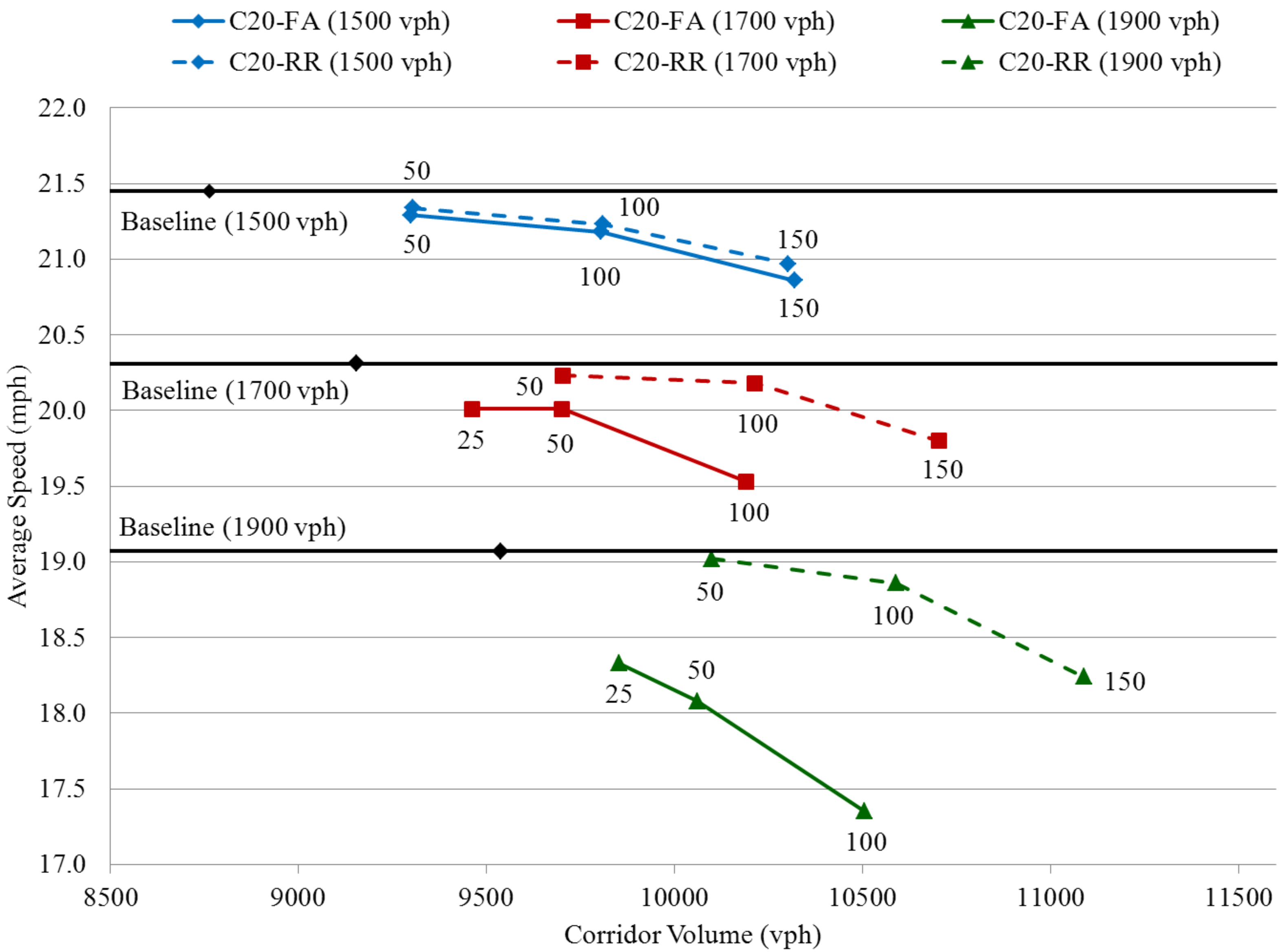

Figure A.2 Corridor Average Speed for Cases C20-FA and C20-RR

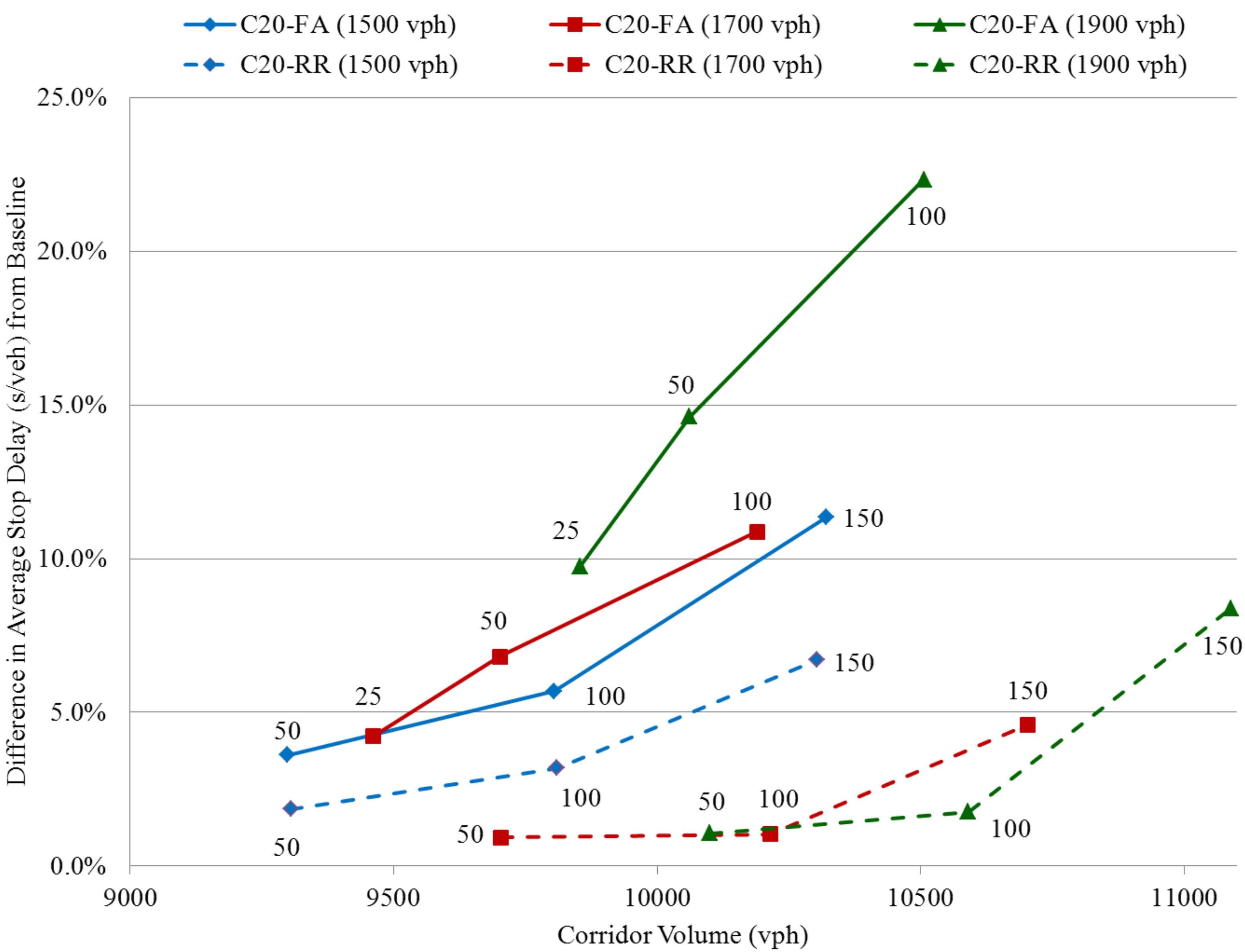

Figure A.3 Corridor-wide Difference in Average Stop Delay for Cases C20-FA and C20-RR

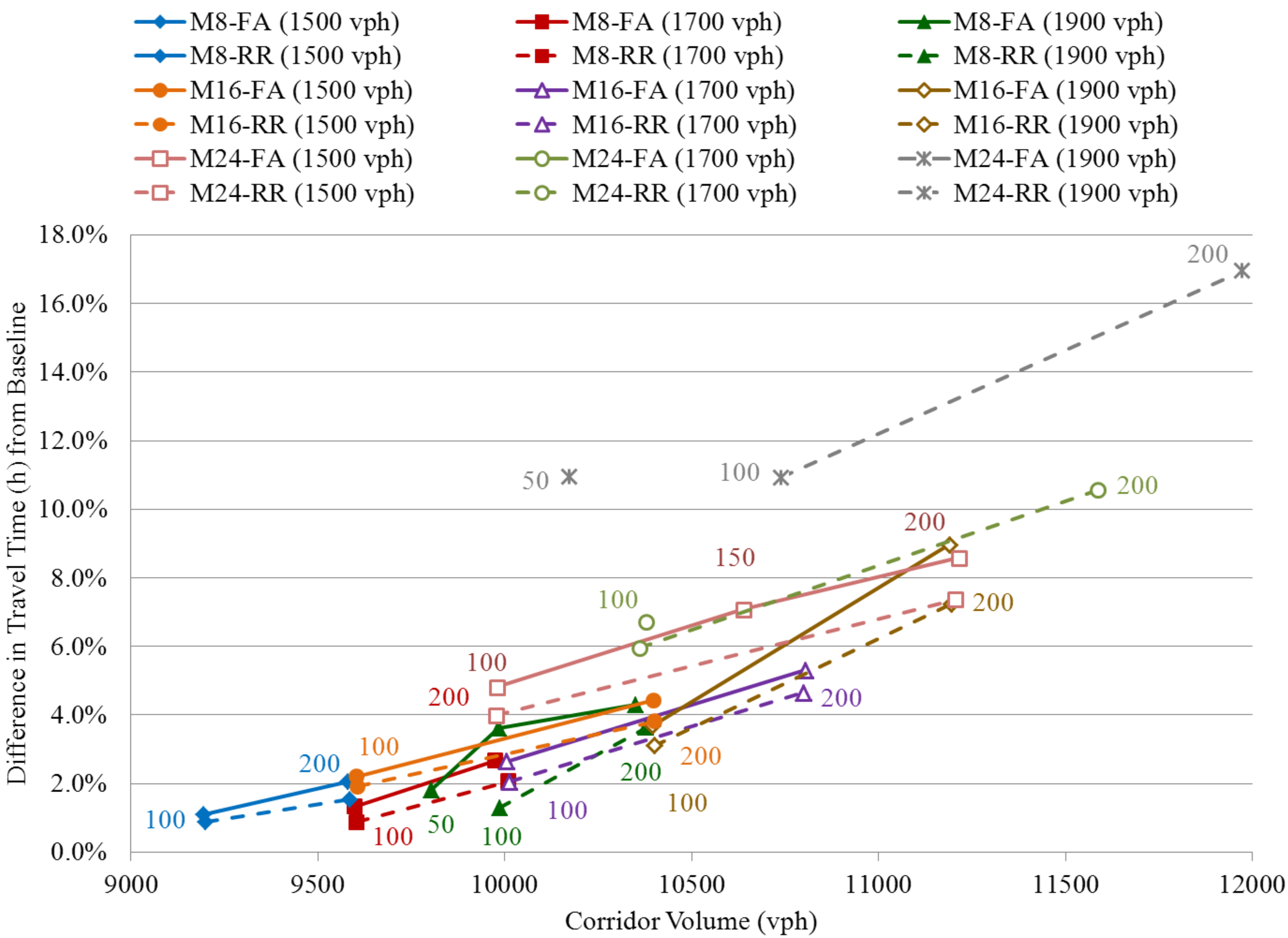

Figure A.4 Corridor-wide Difference in Travel Time for Cases M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR

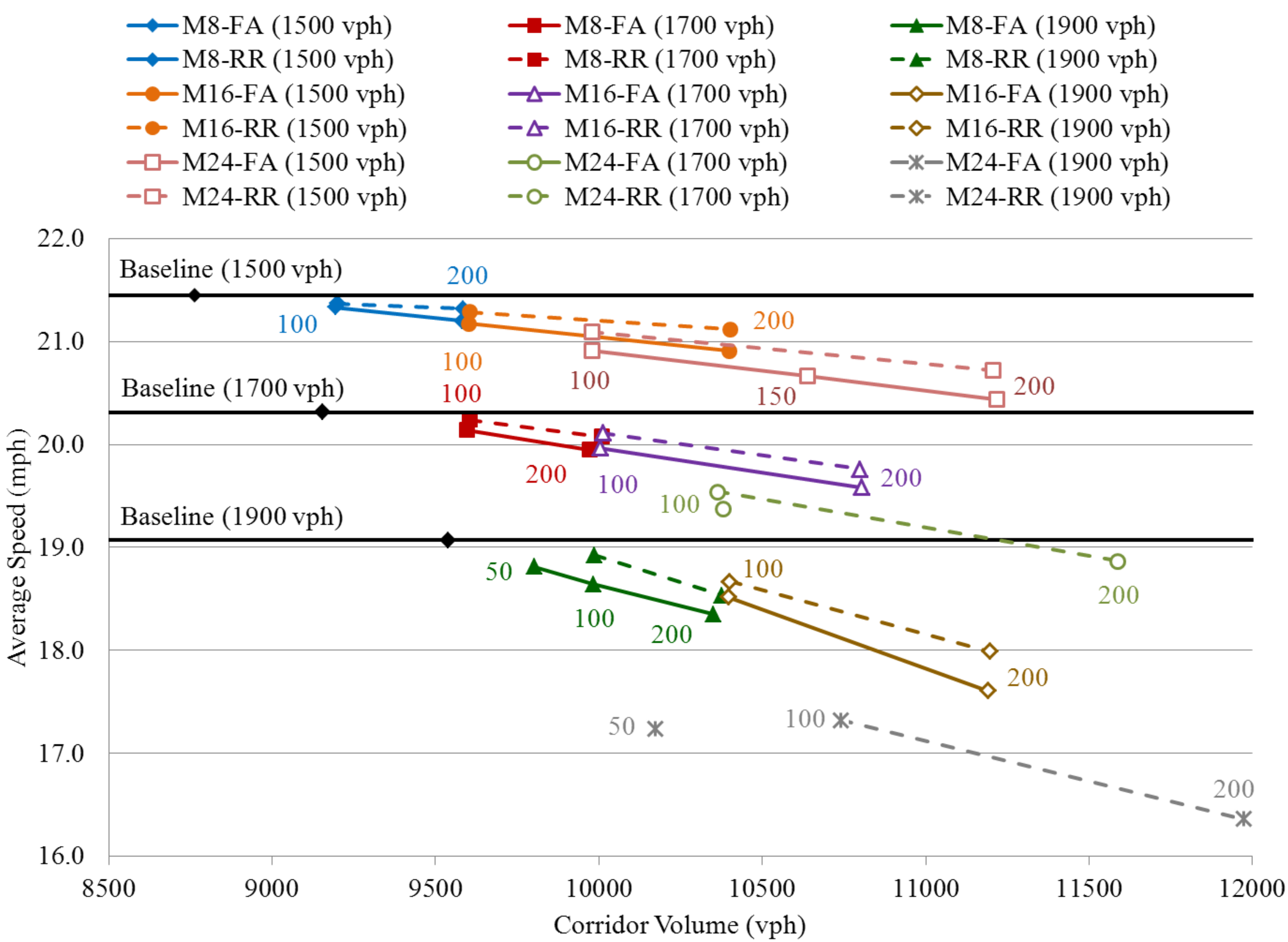

Figure A.5 Corridor Average Speed for Cases M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR

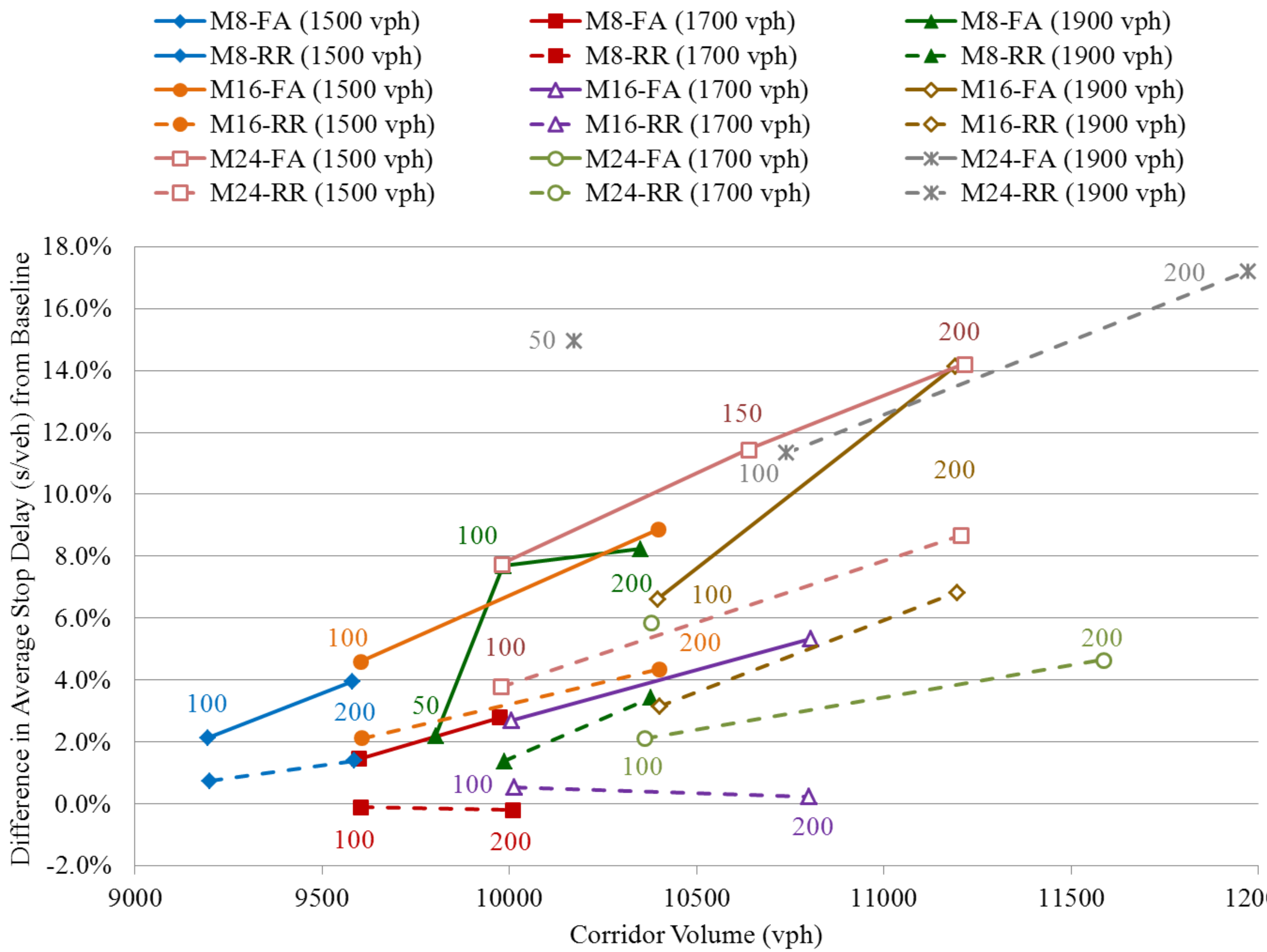

Figure A.6 Corridor-wide Difference in Average Stop Delay for Cases M8-FA, M8-RR, M16-FA, M16-RR, M24-FA, and M24-RR

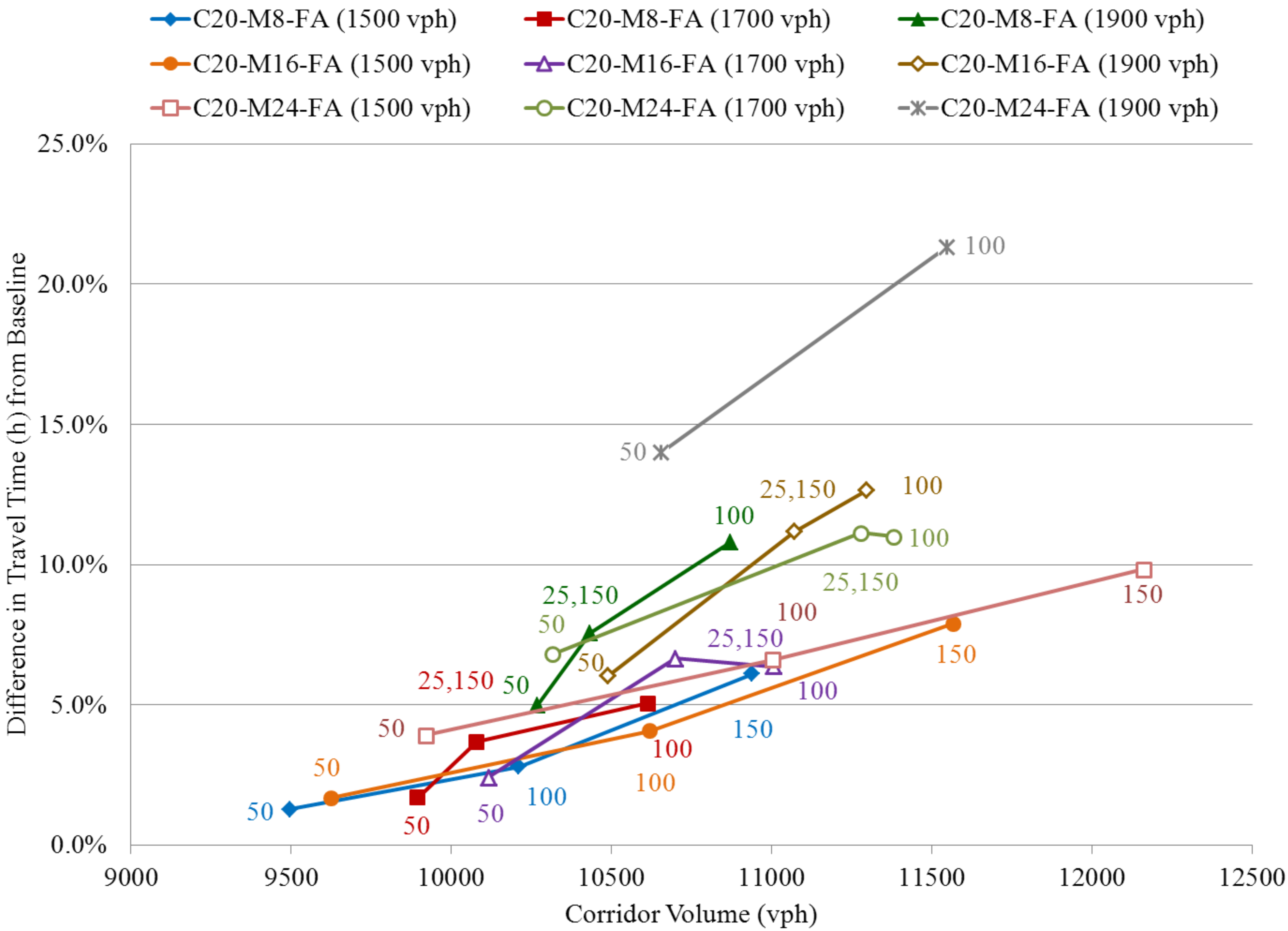

Figure A.7 Corridor-wide Difference in Travel Time for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

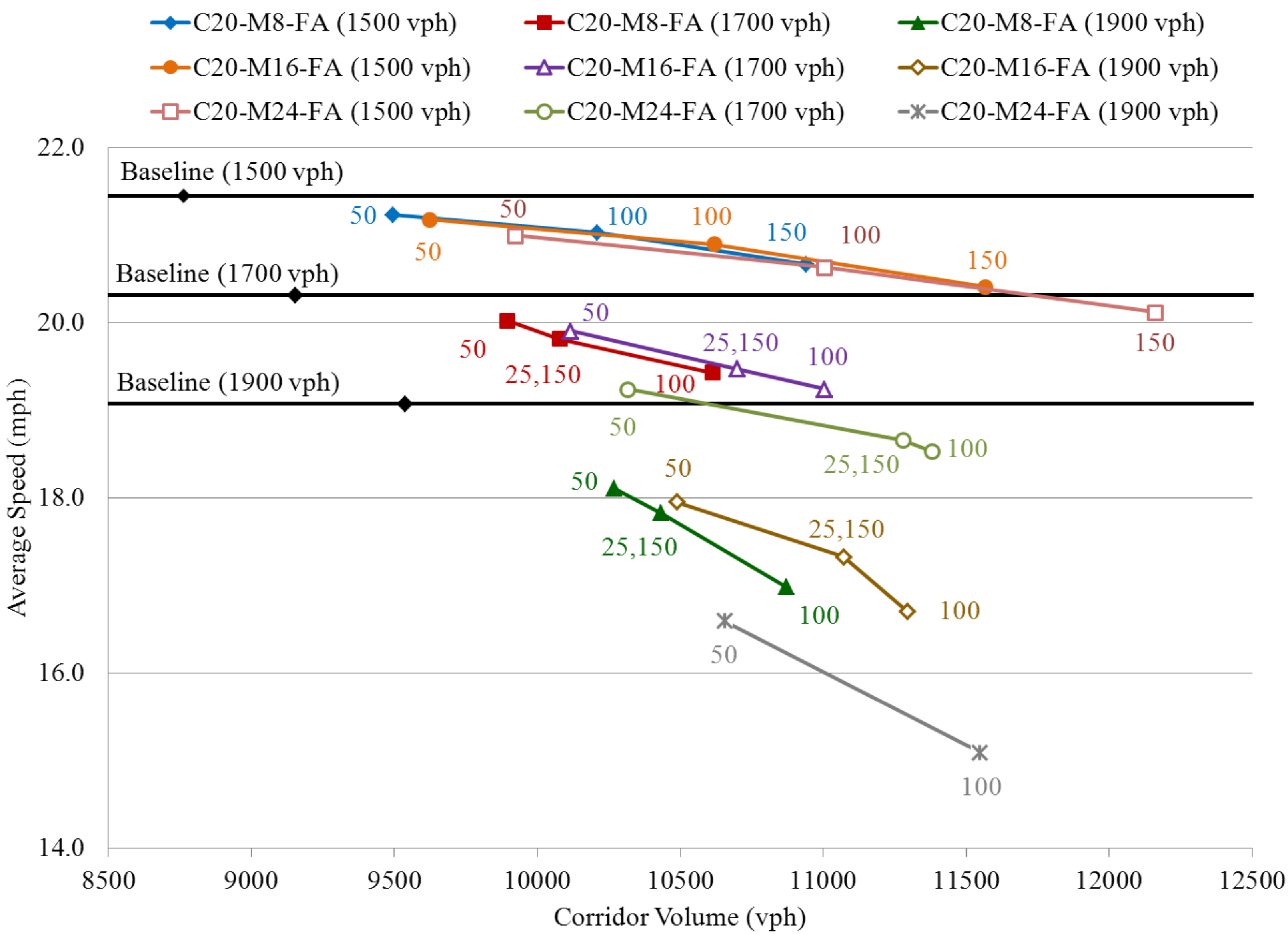

Figure A.8 Corridor Average Speed for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

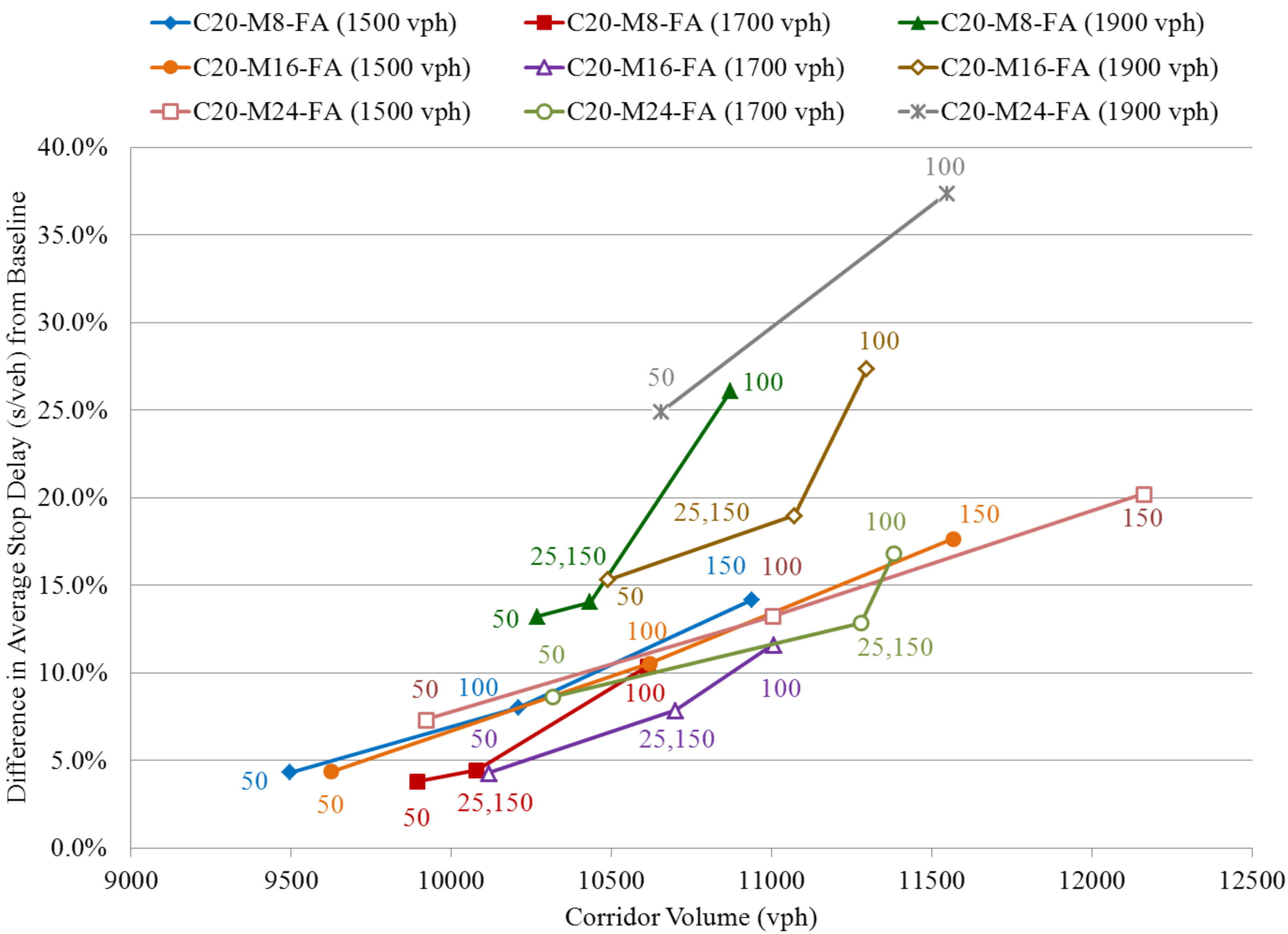

Figure A.9 Corridor-wide Difference in Average Stop Delay for Cases C20-M8-FA, C20-M16-FA, and C20-M24-FA

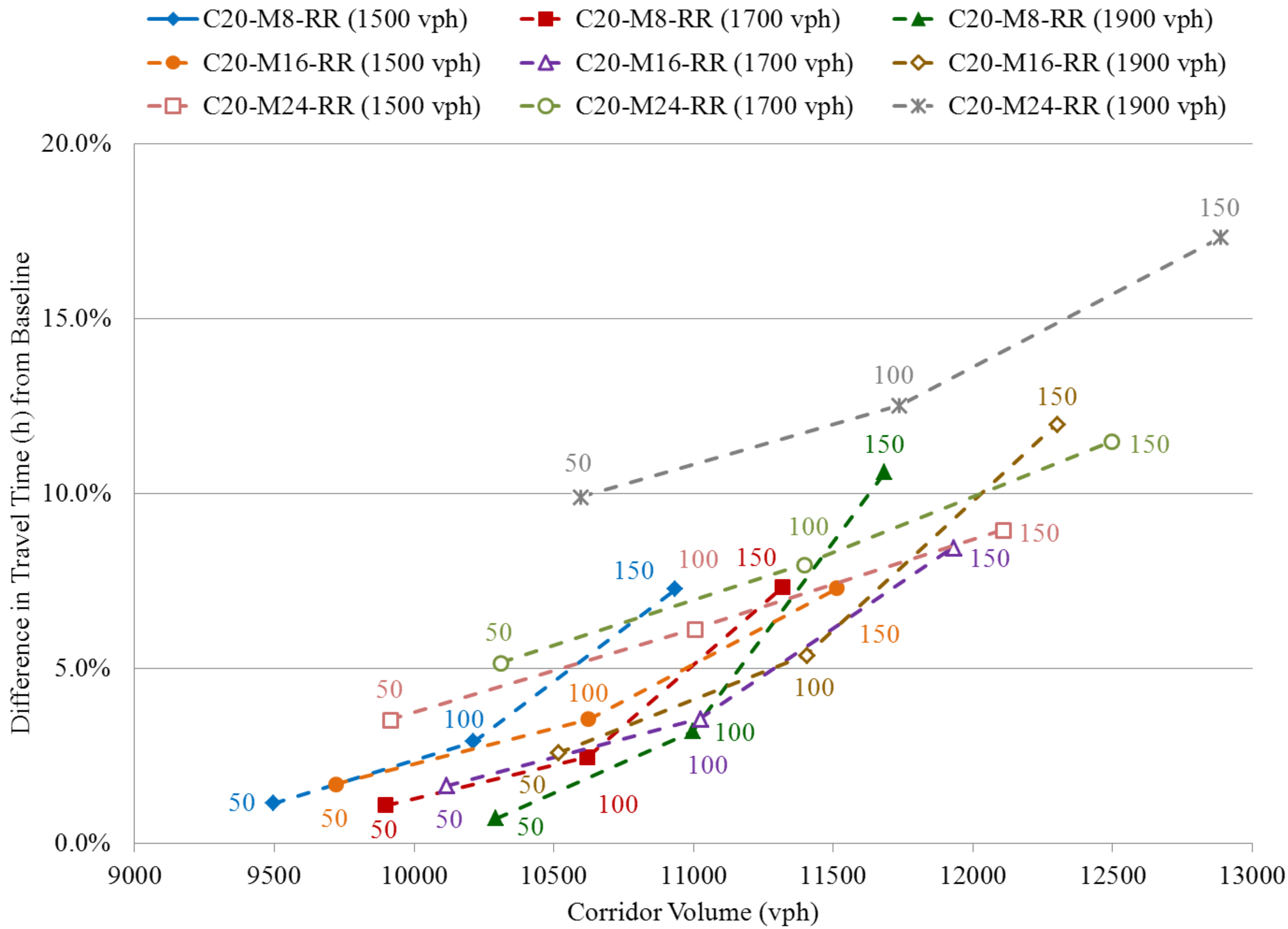

Figure A.10 Corridor-wide Difference in Travel Time for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

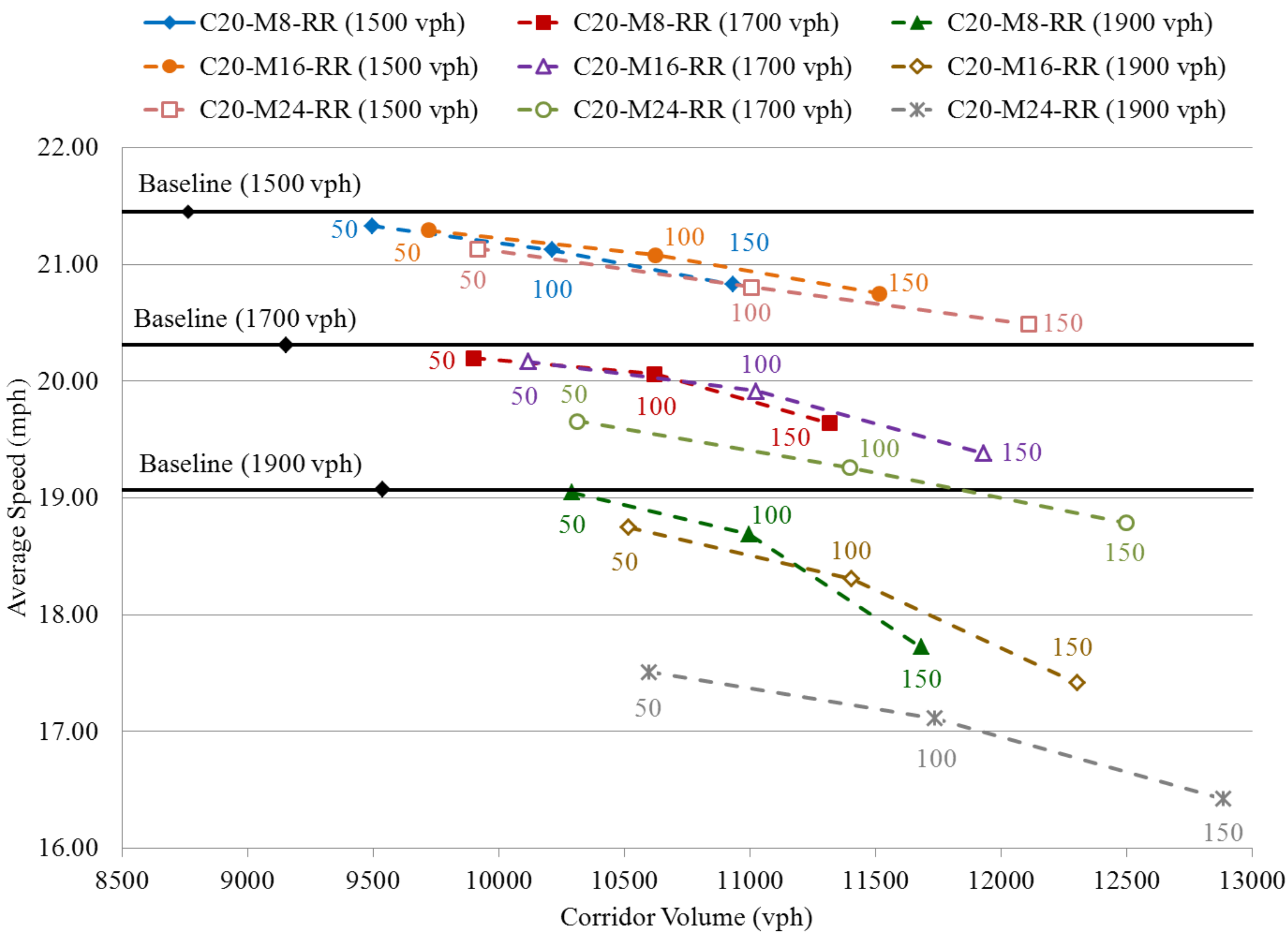

Figure A.11 Corridor Average Speed for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

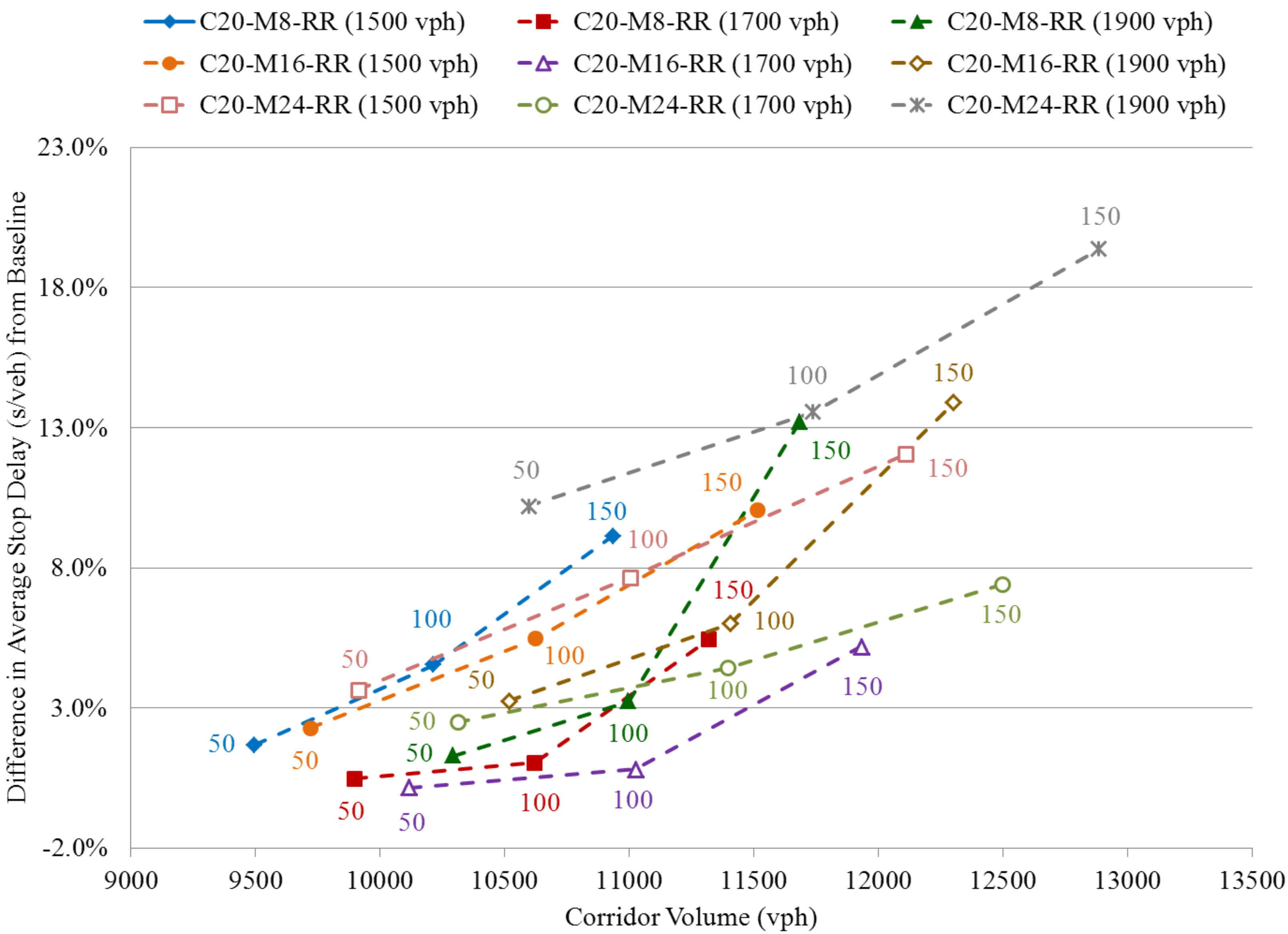

Figure A.12 Corridor-wide Difference in Average Stop Delay for Cases C20-M8-RR, C20-M16-RR, and C20-M24-RR

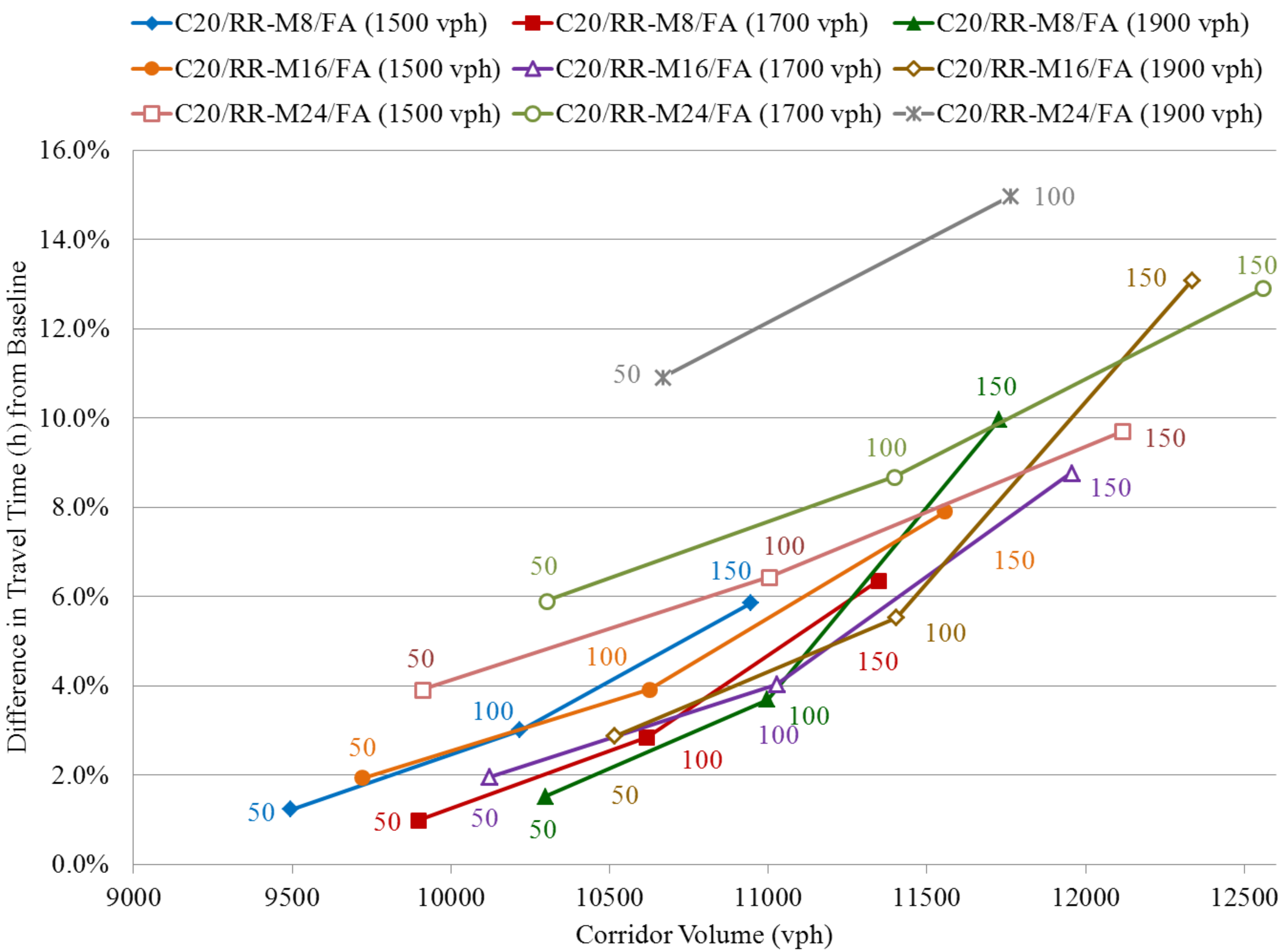

Figure A.13 Corridor-wide Difference in Travel Time for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

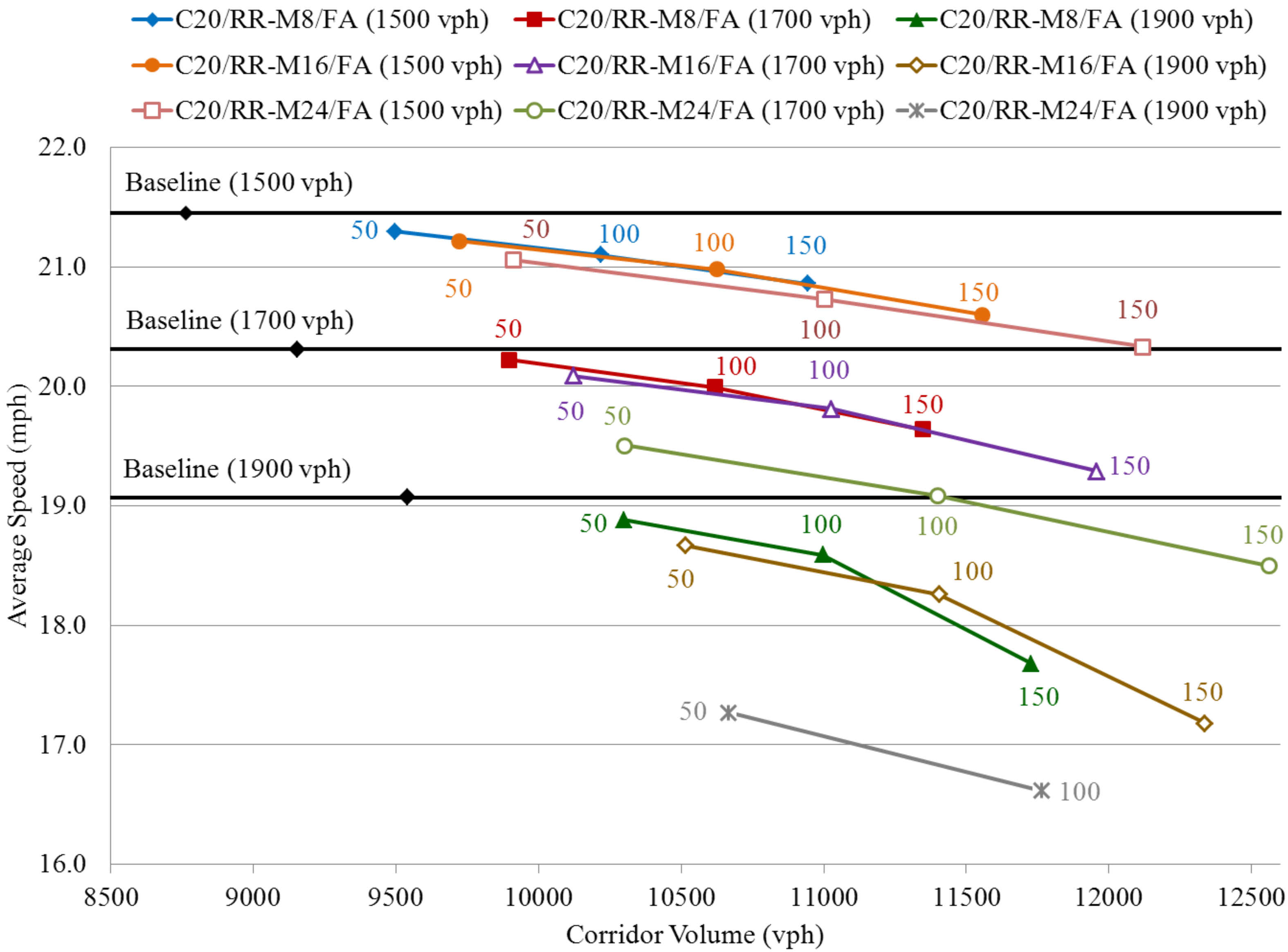

Figure A.14 Corridor Average Speed for C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

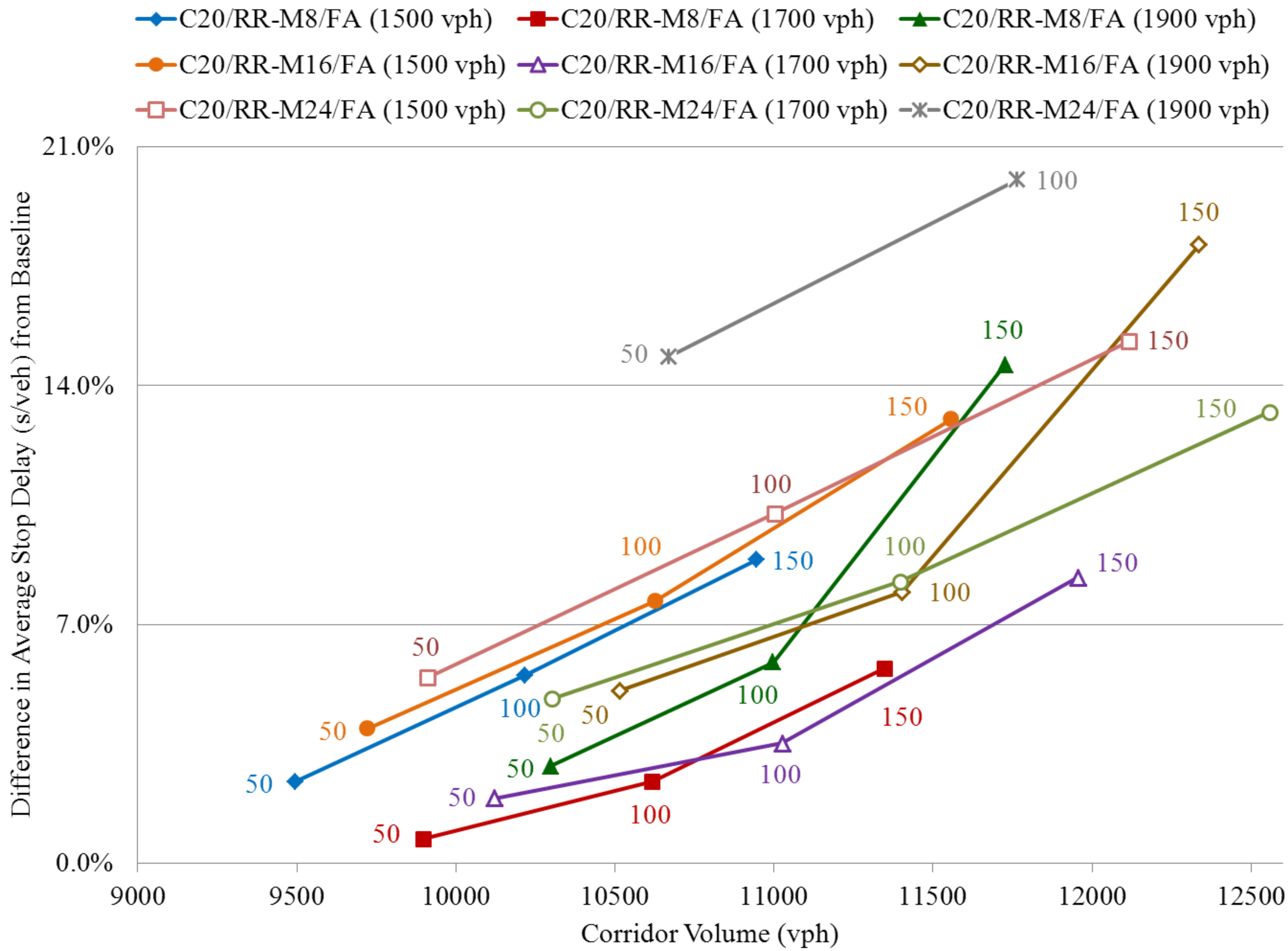

Figure A.15 Corridor-wide Difference in Average Stop Delay for Cases C20/RR-M8/FA, C20/RR-M16/FA, and C20/RR-M24/FA

APPENDIX B

Results for All Low Mainline Volume Cases

Table B.1 Corridor-wide Results for Low Mainline Volume at Baseline

Number of Signalized Intersections	5
Driveway Volume	0
Volume Simulated	8763
Travel Time (h)	330.23
Delay (h)	128.00
Average Speed (mph)	21.45
Average Delay (s/veh)	50.85
Average Stop Delay (s/veh)	23.67

Table B.2 Case C20-FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9299	9805	10321
Difference in Volume Simulated from Baseline	5.8%	10.6%	15.1%
Corridor-wide Travel Time (h)	332.98	335.06	349.80
Difference in Travel Time from Baseline (%)	0.83%	1.44%	5.59%
Corridor-wide Total Delay (h)	137.68	146.23	160.18
Difference in Total Delay from Baseline (%)	7.0%	12.5%	20.1%
Average Speed (mph)	21.29	21.18	20.86
Difference in Average Speed from Baseline (%)	-0.75%	-1.27%	-2.83%
Average Delay (s/veh)	51.65	52.08	54.28
Difference in Average Delay from Baseline (s/veh)	7.2%	12.7%	20.5%
Average Stop Delay (s/veh)	23.14	22.43	22.67
Difference in Average Stop Delay from Baseline (%)	3.41%	5.40%	10.93%
Average Driveway Delay (All Movements, s/veh)	11.34	12.14	13.16
Average Outbound Delay (s/veh)	13.23	14.23	15.18
Average Right-Out Delay (s/veh)	6.55	7.59	8.11
Average Left-Out Delay (s/veh)	19.58	21.27	22.36
Average Left-In Delay (s/veh)	8.29	8.31	9.14
Average Delay in TWLTL (s/veh)	8.29	8.31	9.14
Average Delay for Approach Side Driveways (s/veh)	15.54	16.77	17.67
Average Delay for Departure Side Driveways (s/veh)	9.86	10.48	11.52

Table B.3 Case C20-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9305	9810	10303
Difference in Volume Simulated from Baseline	5.8%	10.7%	14.9%
Corridor-wide Travel Time (h)	333.15	334.64	345.10
Difference in Travel Time from Baseline (%)	0.88%	1.32%	4.31%
Corridor-wide Total Delay (h)	137.41	145.63	160.11
Difference in Total Delay from Baseline (%)	6.8%	12.1%	20.1%
Average Speed (mph)	21.34	21.23	20.97
Difference in Average Speed from Baseline (%)	-0.52%	-1.04%	-2.29%
Average Delay (s/veh)	51.53	51.84	54.31
Difference in Average Delay from Baseline (s/veh)	7.1%	12.4%	20.4%
Average Stop Delay (s/veh)	22.71	21.84	21.58
Difference in Average Stop Delay from Baseline (%)	1.60%	2.88%	6.34%
Average Driveway Delay (All Movements, s/veh)	5.98	6.63	7.32
Average Outbound Delay (s/veh)	5.98	6.63	7.32
Average Right-Out Delay (s/veh)	5.98	6.63	7.32
Average Delay for Approach Side Driveways (s/veh)	8.52	9.37	10.85
Average Delay for Departure Side Driveways (s/veh)	3.44	3.80	3.90

Table B.4 Case M8-FA

MOE	100 vphpd	200 vphpd
Volume Simulated	9195	9581
Difference in Volume Simulated from Baseline	4.7%	8.5%
Corridor-wide Travel Time (h)	333.88	337.14
Difference in Travel Time from Baseline (%)	1.09%	2.05%
Corridor-wide Total Delay (h)	136.64	144.19
Difference in Total Delay from Baseline (%)	6.3%	11.2%
Average Speed (mph)	21.33	21.20
Difference in Average Speed from Baseline (%)	-0.56%	-1.18%
Average Delay (s/veh)	51.80	52.49
Difference in Average Delay from Baseline (s/veh)	6.4%	11.4%
Average Stop Delay (s/veh)	23.05	22.54
Difference in Average Stop Delay from Baseline (%)	2.01%	3.76%
Average Driveway Delay (All Movements, s/veh)	4.42	4.47
Average Outbound Delay (s/veh)	7.90	8.97
Average Right-Out Delay (s/veh)	4.98	5.03
Average Left-Out Delay (s/veh)	10.77	13.62
Average Left-In Delay (s/veh)	5.99	6.16
Average Delay in TWLTL for Merging into Mainline (s/veh)	6.66	7.02
Average Delay in TWLTL (s/veh)	6.62	6.69

Table B.5 Case M8-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	9200	9585
Difference in Volume Simulated from Baseline	4.8%	8.6%
Corridor-wide Travel Time (h)	333.16	335.38
Difference in Travel Time from Baseline (%)	0.88%	1.5%
Corridor-wide Total Delay (h)	135.97	142.28
Difference in Total Delay from Baseline (%)	5.9%	10.0%
Average Speed (mph)	21.37	21.32
Difference in Average Speed from Baseline (%)	-0.37%	-0.6%
Average Delay (s/veh)	51.53	51.82
Difference in Average Delay from Baseline (s/veh)	6.0%	10.3%
Average Stop Delay (s/veh)	22.71	21.94
Difference in Average Stop Delay from Baseline (%)	0.58%	1.1%
Average Driveway Delay (All Movements, s/veh)	1.05	1.10
Average Outbound Delay (s/veh)	4.56	4.90
Average Right-Out Delay (s/veh)	4.56	4.90

Table B.6 Case M16-FA

MOE	100 vphpd	200 vphpd
Volume Simulated	9603	10399
Difference in Volume Simulated from Baseline	8.7%	15.7%
Corridor-wide Travel Time (h)	337.65	345.51
Difference in Travel Time from Baseline (%)	2.2%	4.4%
Corridor-wide Total Delay (h)	144.81	160.92
Difference in Total Delay from Baseline (%)	11.6%	20.5%
Average Speed (mph)	21.17	20.91
Difference in Average Speed from Baseline (%)	-1.3%	-2.6%
Average Delay (s/veh)	52.61	54.11
Difference in Average Delay from Baseline (s/veh)	11.8%	20.8%
Average Stop Delay (s/veh)	22.64	21.89
Difference in Average Stop Delay from Baseline (%)	4.4%	8.5%
Average Driveway Delay (All Movements, s/veh)	4.21	4.38
Average Outbound Delay (s/veh)	8.67	9.60
Average Right-Out Delay (s/veh)	5.14	6.17
Average Left-Out Delay (s/veh)	10.39	12.69
Average Left-In Delay (s/veh)	6.33	6.45
Average Delay in TWLTL for Merging into Mainline (s/veh)	8.18	8.45
Average Delay in TWLTL (s/veh)	7.27	7.46

Table B.7 Case M16-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	9606	10401
Difference in Volume Simulated from Baseline	8.8%	15.7%
Corridor-wide Travel Time (h)	336.67	343.30
Difference in Travel Time from Baseline (%)	1.9%	3.8%
Corridor-wide Total Delay (h)	143.44	158.33
Difference in Total Delay from Baseline (%)	10.8%	19.2%
Average Speed (mph)	21.29	21.12
Difference in Average Speed from Baseline (%)	-0.8%	-1.6%
Average Delay (s/veh)	52.14	53.24
Difference in Average Delay from Baseline (s/veh)	11.0%	19.5%
Average Stop Delay (s/veh)	22.06	20.85
Difference in Average Stop Delay from Baseline (%)	1.8%	3.9%
Average Driveway Delay (All Movements, s/veh)	1.04	1.09
Average Outbound Delay (s/veh)	4.35	4.38
Average Right-Out Delay (s/veh)	4.35	4.38

Table B.8 Case M24-FA

MOE	100 vphpd	150 vphpd	200 vphpd
Volume Simulated	9979	10638	11215
Difference in Volume Simulated from Baseline	12.2%	17.6%	21.9%
Corridor-wide Travel Time (h)	346.90	355.40	361.24
Difference in Travel Time from Baseline (%)	4.8%	7.1%	8.6%
Corridor-wide Total Delay (h)	155.84	170.90	183.61
Difference in Total Delay from Baseline (%)	17.9%	25.1%	30.3%
Average Speed (mph)	20.91	20.67	20.44
Difference in Average Speed from Baseline (%)	-2.6%	-3.8%	-4.9%
Average Delay (s/veh)	54.54	56.21	57.29
Difference in Average Delay from Baseline (s/veh)	18.1%	25.5%	30.6%
Average Stop Delay (s/veh)	22.53	22.02	21.56
Difference in Average Stop Delay from Baseline (%)	7.5%	11.0%	13.8%
Average Driveway Delay (All Movements, s/veh)	3.51	3.92	4.82
Average Outbound Delay (s/veh)	9.28	9.85	11.21
Average Right-Out Delay (s/veh)	5.39	5.80	6.76
Average Left-Out Delay (s/veh)	13.28	13.98	15.66
Average Left-In Delay (s/veh)	6.23	6.67	8.50
Average Delay in TWLTL for Merging into Mainline (s/veh)	8.69	8.83	9.16
Average Delay in TWLTL (s/veh)	7.56	7.57	7.58

Table B.9 Case M24-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	9977	11205
Difference in Volume Simulated from Baseline	12.2%	21.8%
Corridor-wide Travel Time (h)	343.98	356.49
Difference in Travel Time from Baseline (%)	4.0%	7.4%
Corridor-wide Total Delay (h)	153.18	179.26
Difference in Total Delay from Baseline (%)	16.4%	28.6%
Average Speed (mph)	21.09	20.72
Difference in Average Speed from Baseline (%)	-1.7%	-3.5%
Average Delay (s/veh)	53.61	55.94
Difference in Average Delay from Baseline (s/veh)	16.7%	28.9%
Average Stop Delay (s/veh)	21.61	20.27
Difference in Average Stop Delay from Baseline (%)	3.5%	8.3%
Average Driveway Delay (All Movements, s/veh)	1.06	1.10
Average Outbound Delay (s/veh)	5.13	5.64
Average Right-Out Delay (s/veh)	5.13	5.64

Table B.10 Case C20-M8-FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9495	10211	10939
Difference in Volume Simulated from Baseline	7.7%	14.2%	19.9%
Corridor-wide Travel Time (h)	334.51	339.73	351.72
Difference in Travel Time from Baseline (%)	1.3%	2.8%	6.1%
Corridor-wide Total Delay (h)	141.42	155.20	173.32
Difference in Total Delay from Baseline (%)	9.5%	17.5%	26.1%
Average Speed (mph)	21.23	21.03	20.66
Difference in Average Speed from Baseline (%)	-1.0%	-2.0%	-3.8%
Average Delay (s/veh)	51.99	53.12	55.53
Difference in Average Delay from Baseline (s/veh)	9.7%	17.8%	26.6%
Average Stop Delay (s/veh)	22.83	22.08	22.10
Difference in Average Stop Delay from Baseline (%)	4.0%	7.7%	13.6%
Average Driveway Delay (All Movements, s/veh)	7.48	7.66	8.03
Average Outbound Delay (s/veh)	10.95	11.25	12.19
Average Right-Out Delay (s/veh)	6.04	6.50	6.71
Average Left-Out Delay (s/veh)	15.33	15.72	17.51
Average Left-In Delay (s/veh)	7.58	7.89	8.04
Average Delay in TWLTL for Merging into Mainline (s/veh)	6.75	7.30	7.57
Average Delay in TWLTL (s/veh)	7.58	7.89	8.04
Average Delay for Approach Side Driveways (s/veh)	15.51	16.43	17.98
Average Delay for Departure Side Driveways (s/veh)	9.94	10.67	11.49

Table B.11 Case C20-M8-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9496	10213	10935
Difference in Volume Simulated from Baseline	7.7%	14.2%	19.9%
Corridor-wide Travel Time (h)	334.05	340.11	356.07
Difference in Travel Time from Baseline (%)	1.1%	2.9%	7.3%
Corridor-wide Total Delay (h)	140.49	154.56	174.90
Difference in Total Delay from Baseline (%)	8.9%	17.2%	26.8%
Average Speed (mph)	21.33	21.12	20.83
Difference in Average Speed from Baseline (%)	-0.6%	-1.5%	-3.0%
Average Delay (s/veh)	51.64	52.89	55.93
Difference in Average Delay from Baseline (s/veh)	9.1%	17.5%	27.1%
Average Stop Delay (s/veh)	22.22	21.28	20.88
Difference in Average Stop Delay from Baseline (%)	1.4%	4.2%	8.7%
Average Driveway Delay (All Movements, s/veh)	3.71	3.82	4.20
Average Outbound Delay (s/veh)	5.21	5.40	5.64
Average Right-Out Delay (s/veh)	5.21	5.40	5.64
Average Delay for Approach Side Driveways (s/veh)	8.65	9.10	10.46
Average Delay for Departure Side Driveways (s/veh)	3.55	4.04	4.18

Table B.12 Case C20/RR-M8/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9496	10218	10944
Difference in Volume Simulated from Baseline	7.7%	14.2%	19.9%
Corridor-wide Travel Time (h)	334.36	340.47	350.74
Difference in Travel Time from Baseline (%)	1.2%	3.0%	5.8%
Corridor-wide Total Delay (h)	140.92	155.01	171.58
Difference in Total Delay from Baseline (%)	9.2%	17.4%	25.4%
Average Speed (mph)	21.30	21.10	20.86
Difference in Average Speed from Baseline (%)	-0.7%	-1.7%	-2.8%
Average Delay (s/veh)	51.79	53.03	54.91
Difference in Average Delay from Baseline (s/veh)	9.4%	17.8%	25.9%
Average Stop Delay (s/veh)	22.38	21.48	20.80
Difference in Average Stop Delay from Baseline (%)	2.1%	5.1%	8.3%
Average Driveway Delay (All Movements, s/veh)	4.88	4.93	5.36
Average Outbound Delay (s/veh)	7.63	7.95	8.89
Average Right-Out Delay (s/veh)	4.85	4.87	4.90
Average Left-Out Delay (s/veh)	10.02	10.64	12.68
Average Left-In Delay (s/veh)	4.95	6.07	6.21
Average Delay in TWLTL for Merging into Mainline (s/veh)	6.40	6.34	7.13
Average Delay in TWLTL (s/veh)	6.98	7.05	7.98
Average Delay for Approach Side Driveways (s/veh)	8.49	8.95	9.49
Average Delay for Departure Side Driveways (s/veh)	3.51	3.99	4.12

Table B.13 Case C20-M16-FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9624	10619	11566
Difference in Volume Simulated from Baseline	8.9%	17.5%	24.2%
Corridor-wide Travel Time (h)	335.87	344.21	358.55
Difference in Travel Time from Baseline (%)	1.7%	4.1%	7.9%
Corridor-wide Total Delay (h)	145.47	163.66	187.34
Difference in Total Delay from Baseline (%)	12.0%	21.8%	31.7%
Average Speed (mph)	21.18	20.90	20.41
Difference in Average Speed from Baseline (%)	-1.3%	-2.6%	-5.1%
Average Delay (s/veh)	52.28	53.93	56.84
Difference in Average Delay from Baseline (s/veh)	11.4%	22.2%	32.2%
Average Stop Delay (s/veh)	22.53	21.84	21.78
Difference in Average Stop Delay from Baseline (%)	5.0%	10.1%	17.0%
Average Driveway Delay (All Movements, s/veh)	7.58	7.92	7.99
Average Outbound Delay (s/veh)	10.45	11.24	11.72
Average Right-Out Delay (s/veh)	5.76	6.28	6.41
Average Left-Out Delay (s/veh)	14.71	15.99	16.91
Average Left-In Delay (s/veh)	7.86	7.93	8.19
Average Delay in TWLTL for Merging into Mainline (s/veh)	7.30	7.57	8.50
Average Delay in TWLTL (s/veh)	7.86	7.93	8.19
Average Delay for Approach Side Driveways (s/veh)	16.24	17.29	17.48
Average Delay for Departure Side Driveways (s/veh)	10.44	11.06	11.60

Table B.14 Case C20-M16-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9719	10624	11514
Difference in Volume Simulated from Baseline	9.8%	17.5%	23.9%
Corridor-wide Travel Time (h)	335.89	342.37	356.17
Difference in Travel Time from Baseline (%)	1.7%	3.5%	7.3%
Corridor-wide Total Delay (h)	144.56	161.39	183.03
Difference in Total Delay from Baseline (%)	11.5%	20.7%	30.1%
Average Speed (mph)	21.29	21.08	20.75
Difference in Average Speed from Baseline (%)	-0.8%	-1.8%	-3.4%
Average Delay (s/veh)	51.96	53.17	55.69
Difference in Average Delay from Baseline (s/veh)	11.8%	21.1%	30.5%
Average Stop Delay (s/veh)	21.84	20.65	20.03
Difference in Average Stop Delay from Baseline (%)	1.9%	5.0%	9.5%
Average Driveway Delay (All Movements, s/veh)	3.55	3.90	4.03
Average Outbound Delay (s/veh)	5.53	5.67	6.26
Average Right-Out Delay (s/veh)	5.53	5.67	6.26
Average Delay for Approach Side Driveways (s/veh)	8.22	9.12	9.65
Average Delay for Departure Side Driveways (s/veh)	3.75	4.31	4.32

Table B.15 Case C20/RR-M16/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9721	10625	11556
Difference in Volume Simulated from Baseline	9.9%	17.5%	24.2%
Corridor-wide Travel Time (h)	336.77	343.70	358.58
Difference in Travel Time from Baseline (%)	1.9%	3.9%	7.9%
Corridor-wide Total Delay (h)	145.53	162.90	185.84
Difference in Total Delay from Baseline (%)	12.0%	21.4%	31.1%
Average Speed (mph)	21.21	20.98	20.60
Difference in Average Speed from Baseline (%)	-1.1%	-2.3%	-4.1%
Average Delay (s/veh)	52.30	53.65	56.38
Difference in Average Delay from Baseline (s/veh)	12.4%	21.8%	31.6%
Average Stop Delay (s/veh)	22.21	21.15	20.63
Difference in Average Stop Delay from Baseline (%)	3.6%	7.2%	12.4%
Average Driveway Delay (All Movements, s/veh)	4.94	5.06	5.06
Average Outbound Delay (s/veh)	8.26	8.66	9.69
Average Right-Out Delay (s/veh)	5.43	5.80	5.86
Average Left-Out Delay (s/veh)	10.66	11.06	13.27
Average Left-In Delay (s/veh)	6.32	6.40	6.40
Average Delay in TWLTL for Merging into Mainline (s/veh)	6.68	8.39	8.53
Average Delay in TWLTL (s/veh)	7.21	7.37	7.44
Average Delay for Approach Side Driveways (s/veh)	8.31	8.82	9.08
Average Delay for Departure Side Driveways (s/veh)	3.59	4.22	4.50

Table B.16 Case C20-M24-FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9920	11001	12160
Difference in Volume Simulated from Baseline	11.7%	20.3%	27.9%
Corridor-wide Travel Time (h)	343.65	353.56	366.22
Difference in Travel Time from Baseline (%)	3.9%	6.6%	9.8%
Corridor-wide Total Delay (h)	153.10	175.54	202.26
Difference in Total Delay from Baseline (%)	16.4%	27.1%	36.7%
Average Speed (mph)	20.99	20.63	20.12
Difference in Average Speed from Baseline (%)	-2.2%	-4.0%	-6.6%
Average Delay (s/veh)	53.93	55.84	58.37
Difference in Average Delay from Baseline (s/veh)	16.7%	27.5%	37.2%
Average Stop Delay (s/veh)	22.57	21.73	21.38
Difference in Average Stop Delay from Baseline (%)	7.0%	12.8%	19.6%
Average Driveway Delay (All Movements, s/veh)	7.65	7.96	8.16
Average Outbound Delay (s/veh)	11.29	11.95	12.35
Average Right-Out Delay (s/veh)	5.89	6.59	6.74
Average Left-Out Delay (s/veh)	16.46	17.57	18.05
Average Left-In Delay (s/veh)	8.12	7.73	8.32
Average Delay in TWLTL for Merging into Mainline (s/veh)	7.77	7.89	8.50
Average Delay in TWLTL (s/veh)	7.73	8.12	8.32
Average Delay for Approach Side Driveways (s/veh)	16.61	16.96	17.37
Average Delay for Departure Side Driveways (s/veh)	10.84	11.80	12.02

Table B.17 Case C20-M24-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9913	11004	12108
Difference in Volume Simulated from Baseline	11.6%	20.4%	27.6%
Corridor-wide Travel Time (h)	342.30	351.79	362.71
Difference in Travel Time from Baseline (%)	3.5%	6.1%	9.0%
Corridor-wide Total Delay (h)	151.31	173.33	196.55
Difference in Total Delay from Baseline (%)	15.4%	26.2%	34.9%
Average Speed (mph)	21.14	20.81	20.49
Difference in Average Speed from Baseline (%)	-1.5%	-3.1%	-4.7%
Average Delay (s/veh)	53.32	55.14	56.98
Difference in Average Delay from Baseline (s/veh)	15.7%	26.6%	35.4%
Average Stop Delay (s/veh)	21.72	20.41	19.48
Difference in Average Stop Delay from Baseline (%)	3.3%	7.1%	11.3%
Average Driveway Delay (All Movements, s/veh)	3.81	3.94	4.19
Average Outbound Delay (s/veh)	5.71	5.86	6.13
Average Right-Out Delay (s/veh)	5.71	5.86	6.13
Average Delay for Approach Side Driveways (s/veh)	9.01	9.01	9.98
Average Delay for Departure Side Driveways (s/veh)	3.89	4.45	4.59

Table B.18 Case C20/RR-M24/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9910	11003	12115
Difference in Volume Simulated from Baseline	11.6%	20.4%	27.7%
Corridor-wide Travel Time (h)	343.70	352.95	365.73
Difference in Travel Time from Baseline (%)	3.9%	6.4%	9.7%
Corridor-wide Total Delay (h)	152.58	174.46	199.04
Difference in Total Delay from Baseline (%)	16.1%	26.6%	35.7%
Average Speed (mph)	21.06	20.73	20.33
Difference in Average Speed from Baseline (%)	-1.9%	-3.5%	-5.5%
Average Delay (s/veh)	53.76	55.50	57.62
Difference in Average Delay from Baseline (s/veh)	16.4%	27.0%	36.2%
Average Stop Delay (s/veh)	22.13	21.00	20.21
Difference in Average Stop Delay from Baseline (%)	5.2%	9.8%	14.7%
Average Driveway Delay (All Movements, s/veh)	4.83	4.84	5.01
Average Outbound Delay (s/veh)	9.03	9.31	10.14
Average Right-Out Delay (s/veh)	5.54	5.72	5.89
Average Left-Out Delay (s/veh)	12.22	13.20	14.46
Average Left-In Delay (s/veh)	6.97	6.92	6.97
Average Delay in TWLTL for Merging into Mainline (s/veh)	7.91	9.07	9.65
Average Delay in TWLTL (s/veh)	6.67	6.82	7.02
Average Delay for Approach Side Driveways (s/veh)	8.76	8.91	9.38
Average Delay for Departure Side Driveways (s/veh)	3.81	4.21	4.49

APPENDIX C

Results for All Medium Mainline Volume Cases

Table C.1 Corridor-wide Results for Medium Mainline Volume at Baseline

Number of Signalized Intersections	5
Driveway Volume	0
Volume Simulated	9155
Travel Time (h)	378.82
Delay (h)	156.98
Average Speed (mph)	20.31
Average Delay (s/veh)	59.50
Average Stop Delay (s/veh)	37.10

Table C.2 Case C20-FA

MOE	25 vphpd	50 vphpd	100 vphpd
Volume Simulated	9461	9701	10190
Difference in Volume Simulated from Baseline	3.2%	5.6%	10.2%
Corridor-wide Travel Time (h)	389.58	390.80	394.52
Difference in Travel Time from Baseline (%)	2.76%	3.07%	3.98%
Corridor-wide Total Delay (h)	165.05	165.01	170.21
Difference in Total Delay from Baseline (%)	4.9%	4.9%	7.8%
Average Speed (mph)	20.01	20.01	19.53
Difference in Average Speed from Baseline (%)	-1.50%	-1.50%	-3.99%
Average Delay (s/veh)	62.41	62.40	64.12
Difference in Average Delay from Baseline (s/veh)	7.7%	10.0%	16.6%
Average Stop Delay (s/veh)	37.48	37.57	37.40
Difference in Average Stop Delay from Baseline (%)	4.19%	6.61%	10.77%
Average Driveway Delay (All Movements, s/veh)	26.86	29.41	37.36
Average Outbound Delay (s/veh)	36.73	38.85	52.03
Average Right-Out Delay (s/veh)	13.38	16.03	32.00
Average Left-Out Delay (s/veh)	56.37	62.96	73.29
Average Left-In Delay (s/veh)	12.90	13.34	14.20
Average Delay in TWLTL (s/veh)	12.90	13.34	14.20
Average Delay for Approach Side Driveways (s/veh)	46.43	51.12	70.70
Average Delay for Departure Side Driveways (s/veh)	20.12	20.74	24.93

Table C.3 Case C20-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9704	10214	10704
Difference in Volume Simulated from Baseline	5.7%	10.4%	14.5%
Corridor-wide Travel Time (h)	381.68	382.46	398.88
Difference in Travel Time from Baseline (%)	0.75%	0.95%	5.03%
Corridor-wide Total Delay (h)	158.89	159.05	169.33
Difference in Total Delay from Baseline (%)	1.2%	1.3%	7.3%
Average Speed (mph)	20.23	20.18	19.80
Difference in Average Speed from Baseline (%)	-0.40%	-0.64%	-2.58%
Average Delay (s/veh)	60.21	60.27	63.84
Difference in Average Delay from Baseline (s/veh)	6.8%	11.5%	20.3%
Average Stop Delay (s/veh)	35.33	33.60	33.26
Difference in Average Stop Delay from Baseline (%)	0.68%	0.71%	4.25%
Average Driveway Delay (All Movements, s/veh)	9.20	10.18	10.84
Average Outbound Delay (s/veh)	9.20	10.18	10.84
Average Right-Out Delay (s/veh)	9.20	10.18	10.84
Average Delay for Approach Side Driveways (s/veh)	13.94	16.51	17.28
Average Delay for Departure Side Driveways (s/veh)	3.85	4.40	4.47

Table C.4 Case M8-FA

MOE	100 vphpd	200 vphpd
Volume Simulated	9597	9973
Difference in Volume Simulated from Baseline	4.6%	8.2%
Corridor-wide Travel Time (h)	383.92	389.19
Difference in Travel Time from Baseline (%)	1.33%	2.66%
Corridor-wide Total Delay (h)	160.93	164.44
Difference in Total Delay from Baseline (%)	2.5%	4.5%
Average Speed (mph)	20.14	19.95
Difference in Average Speed from Baseline (%)	-0.84%	-1.80%
Average Delay (s/veh)	60.96	62.20
Difference in Average Delay from Baseline (s/veh)	6.9%	12.2%
Average Stop Delay (s/veh)	35.91	35.03
Difference in Average Stop Delay from Baseline (%)	1.32%	2.65%
Average Driveway Delay (All Movements, s/veh)	6.26	7.08
Average Outbound Delay (s/veh)	10.91	13.48
Average Right-Out Delay (s/veh)	5.92	7.34
Average Left-Out Delay (s/veh)	16.48	21.23
Average Left-In Delay (s/veh)	16.48	19.02
Average Delay in TWLTL for Merging into Mainline (s/veh)	8.97	8.98
Average Delay in TWLTL (s/veh)	10.84	12.70

Table C.5 Case M8-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	9604	10010
Difference in Volume Simulated from Baseline	4.7%	8.5%
Corridor-wide Travel Time (h)	382.18	386.78
Difference in Travel Time from Baseline (%)	0.88%	2.1%
Corridor-wide Total Delay (h)	159.31	162.61
Difference in Total Delay from Baseline (%)	1.5%	3.5%
Average Speed (mph)	20.24	20.08
Difference in Average Speed from Baseline (%)	-0.35%	-1.2%
Average Delay (s/veh)	60.37	61.56
Difference in Average Delay from Baseline (s/veh)	6.0%	11.6%
Average Stop Delay (s/veh)	35.33	33.86
Difference in Average Stop Delay from Baseline (%)	-0.28%	-0.4%
Average Driveway Delay (All Movements, s/veh)	1.11	1.13
Average Outbound Delay (s/veh)	5.01	5.67
Average Right-Out Delay (s/veh)	5.01	5.67

Table C.6 Case M16-FA

MOE	100 vphpd	200 vphpd
Volume Simulated	10003	10803
Difference in Volume Simulated from Baseline	8.5%	15.3%
Corridor-wide Travel Time (h)	389.07	400.01
Difference in Travel Time from Baseline (%)	2.6%	5.3%
Corridor-wide Total Delay (h)	164.06	171.38
Difference in Total Delay from Baseline (%)	4.3%	8.4%
Average Speed (mph)	19.97	19.58
Difference in Average Speed from Baseline (%)	-1.7%	-3.7%
Average Delay (s/veh)	62.07	64.50
Difference in Average Delay from Baseline (s/veh)	12.3%	21.8%
Average Stop Delay (s/veh)	34.90	33.21
Difference in Average Stop Delay from Baseline (%)	2.4%	4.9%
Average Driveway Delay (All Movements, s/veh)	7.22	7.73
Average Outbound Delay (s/veh)	11.90	14.70
Average Right-Out Delay (s/veh)	6.48	7.44
Average Left-Out Delay (s/veh)	15.24	19.20
Average Left-In Delay (s/veh)	16.87	19.92
Average Delay in TWLTL for Merging into Mainline (s/veh)	9.22	9.26
Average Delay in TWLTL (s/veh)	12.94	14.17

Table C.7 Case M16-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	10012	10798
Difference in Volume Simulated from Baseline	8.6%	15.2%
Corridor-wide Travel Time (h)	386.75	397.28
Difference in Travel Time from Baseline (%)	2.0%	4.6%
Corridor-wide Total Delay (h)	161.93	168.60
Difference in Total Delay from Baseline (%)	3.1%	6.9%
Average Speed (mph)	20.11	19.76
Difference in Average Speed from Baseline (%)	-1.0%	-2.8%
Average Delay (s/veh)	61.32	63.60
Difference in Average Delay from Baseline (s/veh)	11.3%	20.7%
Average Stop Delay (s/veh)	34.11	31.53
Difference in Average Stop Delay from Baseline (%)	0.2%	-0.1%
Average Driveway Delay (All Movements, s/veh)	1.05	1.10
Average Outbound Delay (s/veh)	5.09	5.11
Average Right-Out Delay (s/veh)	5.09	5.11

Table C.8 Case M24-FA

MOE	100 vphpd
Volume Simulated	10378
Difference in Volume Simulated from Baseline	11.8%
Corridor-wide Travel Time (h)	406.11
Difference in Travel Time from Baseline (%)	6.7%
Corridor-wide Total Delay (h)	176.79
Difference in Total Delay from Baseline (%)	11.2%
Average Speed (mph)	19.38
Difference in Average Speed from Baseline (%)	-4.8%
Average Delay (s/veh)	66.17
Difference in Average Delay from Baseline (s/veh)	20.7%
Average Stop Delay (s/veh)	34.77
Difference in Average Stop Delay from Baseline (%)	5.7%
Average Driveway Delay (All Movements, s/veh)	7.15
Average Outbound Delay (s/veh)	13.79
Average Right-Out Delay (s/veh)	7.83
Average Left-Out Delay (s/veh)	19.93
Average Left-In Delay (s/veh)	18.76
Average Delay in TWLTL for Merging into Mainline (s/veh)	9.86
Average Delay in TWLTL (s/veh)	12.97

Table C.9 Case M24-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	10361	11586
Difference in Volume Simulated from Baseline	11.6%	21.0%
Corridor-wide Travel Time (h)	402.82	423.52
Difference in Travel Time from Baseline (%)	6.0%	10.6%
Corridor-wide Total Delay (h)	173.76	188.08
Difference in Total Delay from Baseline (%)	9.7%	16.5%
Average Speed (mph)	19.54	18.87
Difference in Average Speed from Baseline (%)	-3.9%	-7.6%
Average Delay (s/veh)	65.25	69.34
Difference in Average Delay from Baseline (s/veh)	19.4%	32.2%
Average Stop Delay (s/veh)	33.49	30.74
Difference in Average Stop Delay from Baseline (%)	2.1%	4.4%
Average Driveway Delay (All Movements, s/veh)	1.08	1.13
Average Outbound Delay (s/veh)	6.57	7.74
Average Right-Out Delay (s/veh)	6.57	7.74

Table C.10 Case C20-M8-FA

MOE	50 vphpd	100 vphpd	C25, M150 vphpd
Volume Simulated	9895	10612	10078
Difference in Volume Simulated from Baseline	7.5%	13.7%	9.2%
Corridor-wide Travel Time (h)	385.33	398.97	393.32
Difference in Travel Time from Baseline (%)	1.7%	5.1%	3.7%
Corridor-wide Total Delay (h)	162.10	172.81	167.67
Difference in Total Delay from Baseline (%)	3.2%	9.2%	6.4%
Average Speed (mph)	20.02	19.43	19.82
Difference in Average Speed from Baseline (%)	-1.4%	-4.5%	-2.5%
Average Delay (s/veh)	61.38	64.95	63.29
Difference in Average Delay from Baseline (s/veh)	10.3%	21.0%	14.6%
Average Stop Delay (s/veh)	35.69	35.71	35.27
Difference in Average Stop Delay from Baseline (%)	3.5%	10.0%	4.2%
Average Driveway Delay (All Movements, s/veh)	13.06	13.22	19.07
Average Outbound Delay (s/veh)	20.32	24.76	26.76
Average Right-Out Delay (s/veh)	12.67	20.02	7.84
Average Left-Out Delay (s/veh)	34.14	43.96	24.50
Average Left-In Delay (s/veh)	10.96	11.98	12.79
Average Delay in TWLTL for Merging into Mainline (s/veh)	7.89	8.27	8.23
Average Delay in TWLTL (s/veh)	10.96	11.98	12.79
Average Delay for Approach Side Driveways (s/veh)	48.62	65.64	54.16
Average Delay for Departure Side Driveways (s/veh)	19.40	26.18	18.04

Table C.11 Case C20-M8-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9898	10620	11318
Difference in Volume Simulated from Baseline	7.5%	13.8%	19.1%
Corridor-wide Travel Time (h)	382.97	388.40	408.71
Difference in Travel Time from Baseline (%)	1.1%	2.5%	7.3%
Corridor-wide Total Delay (h)	159.51	162.27	174.67
Difference in Total Delay from Baseline (%)	1.6%	3.3%	10.1%
Average Speed (mph)	20.20	20.06	19.64
Difference in Average Speed from Baseline (%)	-0.6%	-1.2%	-3.4%
Average Delay (s/veh)	60.44	61.44	65.53
Difference in Average Delay from Baseline (s/veh)	9.0%	16.5%	26.6%
Average Stop Delay (s/veh)	34.48	32.32	31.74
Difference in Average Stop Delay from Baseline (%)	0.2%	0.6%	4.9%
Average Driveway Delay (All Movements, s/veh)	5.17	5.74	6.52
Average Outbound Delay (s/veh)	6.53	7.48	8.82
Average Right-Out Delay (s/veh)	6.53	7.48	8.82
Average Delay for Approach Side Driveways (s/veh)	13.91	16.91	19.39
Average Delay for Departure Side Driveways (s/veh)	3.86	4.11	4.49

Table C.12 Case C20/RR-M8/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	9898	10618	11347
Difference in Volume Simulated from Baseline	7.5%	13.8%	19.3%
Corridor-wide Travel Time (h)	382.58	389.91	404.55
Difference in Travel Time from Baseline (%)	1.0%	2.8%	6.4%
Corridor-wide Total Delay (h)	159.18	163.79	172.73
Difference in Total Delay from Baseline (%)	1.4%	4.2%	9.1%
Average Speed (mph)	20.22	19.99	19.64
Difference in Average Speed from Baseline (%)	-0.4%	-1.6%	-3.4%
Average Delay (s/veh)	60.32	61.97	64.92
Difference in Average Delay from Baseline (s/veh)	8.8%	17.2%	26.1%
Average Stop Delay (s/veh)	34.56	32.77	31.74
Difference in Average Stop Delay from Baseline (%)	0.4%	2.0%	5.1%
Average Driveway Delay (All Movements, s/veh)	7.09	7.80	8.69
Average Outbound Delay (s/veh)	9.12	11.14	12.89
Average Right-Out Delay (s/veh)	4.43	5.96	6.60
Average Left-Out Delay (s/veh)	13.23	15.62	18.84
Average Left-In Delay (s/veh)	14.32	17.30	19.79
Average Delay in TWLTL for Merging into Mainline (s/veh)	8.56	9.08	9.36
Average Delay in TWLTL (s/veh)	10.05	11.37	13.26
Average Delay for Approach Side Driveways (s/veh)	13.80	17.02	18.37
Average Delay for Departure Side Driveways (s/veh)	3.82	4.37	4.55

Table C.13 Case C20-M16-FA

MOE	50 vphpd	100 vphpd	C25, M150 vphpd
Volume Simulated	10116	11004	10699
Difference in Volume Simulated from Baseline	9.5%	16.8%	14.4%
Corridor-wide Travel Time (h)	388.16	404.63	405.80
Difference in Travel Time from Baseline (%)	2.4%	6.4%	6.6%
Corridor-wide Total Delay (h)	164.12	176.52	175.64
Difference in Total Delay from Baseline (%)	4.3%	11.1%	10.6%
Average Speed (mph)	19.91	19.24	19.47
Difference in Average Speed from Baseline (%)	-2.0%	-5.6%	-4.3%
Average Delay (s/veh)	62.09	66.09	65.82
Difference in Average Delay from Baseline (s/veh)	13.3%	25.1%	22.6%
Average Stop Delay (s/veh)	35.08	34.92	34.45
Difference in Average Stop Delay from Baseline (%)	4.0%	11.3%	7.5%
Average Driveway Delay (All Movements, s/veh)	16.78	22.86	9.15
Average Outbound Delay (s/veh)	22.81	32.02	16.07
Average Right-Out Delay (s/veh)	10.33	19.59	7.18
Average Left-Out Delay (s/veh)	29.27	30.49	39.56
Average Left-In Delay (s/veh)	12.71	12.75	14.11
Average Delay in TWLTL for Merging into Mainline (s/veh)	8.29	8.83	9.04
Average Delay in TWLTL (s/veh)	12.71	12.75	14.11
Average Delay for Approach Side Driveways (s/veh)	53.34	71.64	55.49
Average Delay for Departure Side Driveways (s/veh)	20.56	29.18	19.17

Table C.14 Case C20-M16-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10116	11024	11930
Difference in Volume Simulated from Baseline	9.5%	17.0%	23.3%
Corridor-wide Travel Time (h)	385.18	392.80	413.81
Difference in Travel Time from Baseline (%)	1.7%	3.6%	8.5%
Corridor-wide Total Delay (h)	160.53	165.00	178.50
Difference in Total Delay from Baseline (%)	2.2%	4.9%	12.1%
Average Speed (mph)	20.17	19.92	19.38
Difference in Average Speed from Baseline (%)	-0.7%	-2.0%	-4.8%
Average Delay (s/veh)	60.82	62.39	66.67
Difference in Average Delay from Baseline (s/veh)	11.5%	20.8%	31.5%
Average Stop Delay (s/veh)	33.63	31.06	30.03
Difference in Average Stop Delay from Baseline (%)	-0.2%	0.2%	4.5%
Average Driveway Delay (All Movements, s/veh)	5.09	5.75	6.63
Average Outbound Delay (s/veh)	6.66	7.62	9.11
Average Right-Out Delay (s/veh)	6.66	7.62	9.11
Average Delay for Approach Side Driveways (s/veh)	13.84	16.23	19.13
Average Delay for Departure Side Driveways (s/veh)	4.39	4.58	5.17

Table C.15 Case C20/RR-M16/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10120	11025	11956
Difference in Volume Simulated from Baseline	9.5%	17.0%	23.4%
Corridor-wide Travel Time (h)	386.40	394.76	415.27
Difference in Travel Time from Baseline (%)	2.0%	4.0%	8.8%
Corridor-wide Total Delay (h)	161.76	166.81	179.81
Difference in Total Delay from Baseline (%)	3.0%	5.9%	12.7%
Average Speed (mph)	20.09	19.81	19.29
Difference in Average Speed from Baseline (%)	-1.1%	-2.5%	-5.3%
Average Delay (s/veh)	61.26	63.01	67.05
Difference in Average Delay from Baseline (s/veh)	12.1%	21.6%	32.1%
Average Stop Delay (s/veh)	34.21	31.93	31.00
Difference in Average Stop Delay from Baseline (%)	1.5%	2.9%	7.8%
Average Driveway Delay (All Movements, s/veh)	7.89	8.46	8.83
Average Outbound Delay (s/veh)	9.45	11.79	12.96
Average Right-Out Delay (s/veh)	4.82	5.55	6.32
Average Left-Out Delay (s/veh)	13.39	17.06	19.15
Average Left-In Delay (s/veh)	15.73	17.94	21.12
Average Delay in TWLTL for Merging into Mainline (s/veh)	8.63	9.09	9.41
Average Delay in TWLTL (s/veh)	12.83	13.52	14.18
Average Delay for Approach Side Driveways (s/veh)	13.99	16.72	17.16
Average Delay for Departure Side Driveways (s/veh)	3.92	4.31	4.88

Table C.16 Case C20-M24-FA

MOE	50 vphpd	100 vphpd	C25, M150 vphpd
Volume Simulated	10314	11381	11278
Difference in Volume Simulated from Baseline	11.2%	19.6%	18.8%
Corridor-wide Travel Time (h)	406.46	425.66	426.28
Difference in Travel Time from Baseline (%)	6.8%	11.0%	11.1%
Corridor-wide Total Delay (h)	178.41	192.70	192.00
Difference in Total Delay from Baseline (%)	12.0%	18.5%	18.2%
Average Speed (mph)	19.24	18.53	18.66
Difference in Average Speed from Baseline (%)	-5.5%	-9.6%	-8.9%
Average Delay (s/veh)	66.65	70.53	70.35
Difference in Average Delay from Baseline (s/veh)	20.8%	32.1%	31.3%
Average Stop Delay (s/veh)	36.04	35.88	34.56
Difference in Average Stop Delay from Baseline (%)	8.4%	16.6%	12.7%
Average Driveway Delay (All Movements, s/veh)	20.52	27.50	9.22
Average Outbound Delay (s/veh)	29.20	39.18	19.75
Average Right-Out Delay (s/veh)	13.89	24.77	10.10
Average Left-Out Delay (s/veh)	43.85	54.24	29.48
Average Left-In Delay (s/veh)	14.01	13.48	14.16
Average Delay in TWLTL for Merging into Mainline (s/veh)	6.50	7.13	7.08
Average Delay in TWLTL (s/veh)	13.48	14.01	14.16
Average Delay for Approach Side Driveways (s/veh)	64.28	91.78	52.76
Average Delay for Departure Side Driveways (s/veh)	21.83	28.35	20.54

Table C.17 Case C20-M24-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10309	11394	12495
Difference in Volume Simulated from Baseline	11.2%	19.7%	26.7%
Corridor-wide Travel Time (h)	399.43	411.60	427.99
Difference in Travel Time from Baseline (%)	5.2%	8.0%	11.5%
Corridor-wide Total Delay (h)	171.37	179.23	189.92
Difference in Total Delay from Baseline (%)	8.4%	12.4%	17.3%
Average Speed (mph)	19.66	19.26	18.79
Difference in Average Speed from Baseline (%)	-3.3%	-5.5%	-8.1%
Average Delay (s/veh)	64.50	66.89	69.82
Difference in Average Delay from Baseline (s/veh)	18.1%	28.5%	37.6%
Average Stop Delay (s/veh)	33.79	31.19	29.36
Difference in Average Stop Delay from Baseline (%)	2.3%	4.0%	6.9%
Average Driveway Delay (All Movements, s/veh)	5.85	6.73	7.54
Average Outbound Delay (s/veh)	8.58	9.32	10.42
Average Right-Out Delay (s/veh)	8.58	9.32	10.42
Average Delay for Approach Side Driveways (s/veh)	15.85	19.80	22.00
Average Delay for Departure Side Driveways (s/veh)	4.64	5.11	5.85

Table C.18 Case C20/RR-M24/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10300	11398	12559
Difference in Volume Simulated from Baseline	11.1%	19.7%	27.1%
Corridor-wide Travel Time (h)	402.60	414.86	435.00
Difference in Travel Time from Baseline (%)	5.9%	8.7%	12.9%
Corridor-wide Total Delay (h)	174.12	182.37	195.95
Difference in Total Delay from Baseline (%)	9.8%	13.9%	19.9%
Average Speed (mph)	19.51	19.08	18.50
Difference in Average Speed from Baseline (%)	-4.1%	-6.4%	-9.8%
Average Delay (s/veh)	65.36	67.78	71.33
Difference in Average Delay from Baseline (s/veh)	19.1%	29.5%	39.2%
Average Stop Delay (s/veh)	34.65	32.48	31.17
Difference in Average Stop Delay from Baseline (%)	4.7%	7.8%	12.6%
Average Driveway Delay (All Movements, s/veh)	8.33	8.94	9.32
Average Outbound Delay (s/veh)	12.81	13.49	16.55
Average Right-Out Delay (s/veh)	6.85	7.59	9.11
Average Left-Out Delay (s/veh)	18.59	19.55	24.13
Average Left-In Delay (s/veh)	18.90	20.46	22.48
Average Delay in TWLTL for Merging into Mainline (s/veh)	9.12	9.87	9.56
Average Delay in TWLTL (s/veh)	13.21	13.87	14.33
Average Delay for Approach Side Driveways (s/veh)	15.83	18.81	19.70
Average Delay for Departure Side Driveways (s/veh)	4.34	4.52	5.04

APPENDIX D

Results for All High Mainline Volume Cases

Table D.1 Corridor-wide Results for High Mainline Volume at Baseline

Number of Signalized Intersections	5
Driveway Volume	0
Volume Simulated	9539
Travel Time (h)	435.56
Delay (h)	194.27
Average Speed (mph)	19.07
Average Delay (s/veh)	70.29
Average Stop Delay (s/veh)	44.75

Table D.2 Case C20-FA

MOE	25 vphpd	50 vphpd	100 vphpd
Volume Simulated	9853	10061	10506
Difference in Volume Simulated from Baseline	3.2%	5.2%	9.2%
Corridor-wide Travel Time (h)	458.11	458.43	475.60
Difference in Travel Time from Baseline (%)	4.92%	100.0%	8.42%
Corridor-wide Total Delay (h)	213.67	215.09	231.15
Difference in Total Delay from Baseline (%)	9.1%	9.7%	16.0%
Average Speed (mph)	18.33	18.08	17.35
Difference in Average Speed from Baseline (%)	-4.04%	100.0%	-9.91%
Average Delay (s/veh)	76.67	77.09	81.50
Difference in Average Delay from Baseline (s/veh)	11.2%	13.6%	21.7%
Average Stop Delay (s/veh)	48.00	49.69	52.32
Difference in Average Stop Delay from Baseline (%)	9.78%	100.0%	22.36%
Average Driveway Delay (All Movements, s/veh)	77.70	112.82	125.92
Average Outbound Delay (s/veh)	107.40	178.52	193.84
Average Right-Out Delay (s/veh)	56.07	122.25	154.87
Average Left-Out Delay (s/veh)	156.28	233.25	235.39
Average Left-In Delay (s/veh)	18.62	18.78	19.36
Average Delay in TWLTL (s/veh)	18.62	18.78	19.36
Average Delay for Approach Side Driveways (s/veh)	156.93	250.48	264.44
Average Delay for Departure Side Driveways (s/veh)	46.63	69.28	82.46

Table D.3 Case C20-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10100	10590	11089
Difference in Volume Simulated from Baseline	5.6%	9.9%	14.0%
Corridor-wide Travel Time (h)	438.09	441.81	466.76
Difference in Travel Time from Baseline (%)	0.58%	1.41%	6.68%
Corridor-wide Total Delay (h)	195.97	198.57	216.33
Difference in Total Delay from Baseline (%)	0.9%	2.2%	10.2%
Average Speed (mph)	19.02	18.86	18.24
Difference in Average Speed from Baseline (%)	-0.26%	-1.11%	-4.55%
Average Delay (s/veh)	70.90	71.81	77.46
Difference in Average Delay from Baseline (s/veh)	6.4%	11.8%	21.9%
Average Stop Delay (s/veh)	42.72	41.03	42.02
Difference in Average Stop Delay from Baseline (%)	0.74%	1.44%	7.99%
Average Driveway Delay (All Movements, s/veh)	15.39	17.26	22.13
Average Outbound Delay (s/veh)	15.39	17.26	22.13
Average Right-Out Delay (s/veh)	15.39	17.26	22.13
Average Delay for Approach Side Driveways (s/veh)	24.79	28.96	37.97
Average Delay for Departure Side Driveways (s/veh)	5.55	5.99	6.28

Table D.4 Case M8-FA

MOE	50 vphpd	100 vphpd	200 vphpd
Volume Simulated	9803	9983	10350
Difference in Volume Simulated from Baseline	2.7%	4.4%	7.8%
Corridor-wide Travel Time (h)	441.85	443.59	455.09
Difference in Travel Time from Baseline (%)	1.42%	1.81%	4.29%
Corridor-wide Total Delay (h)	207.51	201.09	210.88
Difference in Total Delay from Baseline (%)	6.4%	3.4%	7.9%
Average Speed (mph)	18.84	18.81	18.35
Difference in Average Speed from Baseline (%)	-1.22%	-1.38%	-3.92%
Average Delay (s/veh)	74.77	72.67	75.83
Difference in Average Delay from Baseline (s/veh)	8.5%	7.6%	14.6%
Average Stop Delay (s/veh)	45.32	44.52	44.94
Difference in Average Stop Delay from Baseline (%)	3.74%	3.84%	8.23%
Average Driveway Delay (All Movements, s/veh)	10.65	13.15	16.09
Average Outbound Delay (s/veh)	28.95	29.63	37.91
Average Right-Out Delay (s/veh)	12.90	17.53	20.88
Average Left-Out Delay (s/veh)	37.05	38.66	47.06
Average Left-In Delay (s/veh)	25.13	28.98	36.54
Average Delay in TWLTL for Merging into Mainline (s/veh)	8.17	9.90	11.47
Average Delay in TWLTL (s/veh)	18.88	20.10	22.11

Table D.5 Case M8-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	9986	10377
Difference in Volume Simulated from Baseline	4.5%	8.1%
Corridor-wide Travel Time (h)	441.25	451.90
Difference in Travel Time from Baseline (%)	1.29%	3.6%
Corridor-wide Total Delay (h)	198.84	207.38
Difference in Total Delay from Baseline (%)	2.3%	6.3%
Average Speed (mph)	18.92	18.53
Difference in Average Speed from Baseline (%)	-0.78%	-2.9%
Average Delay (s/veh)	71.90	74.73
Difference in Average Delay from Baseline (s/veh)	6.6%	13.5%
Average Stop Delay (s/veh)	43.34	42.59
Difference in Average Stop Delay from Baseline (%)	1.27%	3.3%
Average Driveway Delay (All Movements, s/veh)	1.12	1.31
Average Outbound Delay (s/veh)	10.21	10.73
Average Right-Out Delay (s/veh)	10.21	10.73

Table D.6 Case M16-FA

MOE	100 vphpd	200 vphpd
Volume Simulated	10396	11190
Difference in Volume Simulated from Baseline	8.2%	14.8%
Corridor-wide Travel Time (h)	452.27	478.41
Difference in Travel Time from Baseline (%)	3.7%	9.0%
Corridor-wide Total Delay (h)	207.58	228.87
Difference in Total Delay from Baseline (%)	6.4%	15.1%
Average Speed (mph)	18.52	17.61
Difference in Average Speed from Baseline (%)	-3.0%	-8.3%
Average Delay (s/veh)	74.80	80.92
Difference in Average Delay from Baseline (s/veh)	13.8%	25.9%
Average Stop Delay (s/veh)	43.97	44.42
Difference in Average Stop Delay from Baseline (%)	6.4%	13.9%
Average Driveway Delay (All Movements, s/veh)	10.98	11.82
Average Outbound Delay (s/veh)	30.47	37.40
Average Right-Out Delay (s/veh)	17.62	27.73
Average Left-Out Delay (s/veh)	27.07	32.67
Average Left-In Delay (s/veh)	29.68	37.66
Average Delay in TWLTL for Merging into Mainline (s/veh)	14.93	15.25
Average Delay in TWLTL (s/veh)	24.16	28.48

Table D.7 Case M16-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	10400	11196
Difference in Volume Simulated from Baseline	8.3%	14.8%
Corridor-wide Travel Time (h)	449.48	469.57
Difference in Travel Time from Baseline (%)	3.1%	7.2%
Corridor-wide Total Delay (h)	204.74	220.40
Difference in Total Delay from Baseline (%)	5.1%	11.9%
Average Speed (mph)	18.67	17.99
Difference in Average Speed from Baseline (%)	-2.2%	-6.0%
Average Delay (s/veh)	73.88	78.62
Difference in Average Delay from Baseline (s/veh)	12.7%	23.8%
Average Stop Delay (s/veh)	42.38	40.93
Difference in Average Stop Delay from Baseline (%)	2.8%	6.5%
Average Driveway Delay (All Movements, s/veh)	1.10	1.21
Average Outbound Delay (s/veh)	11.53	15.75
Average Right-Out Delay (s/veh)	11.53	15.75

Table D.8 Case M24-FA

MOE	50 vphpd
Volume Simulated	10172
Difference in Volume Simulated from Baseline	6.2%
Corridor-wide Travel Time (h)	489.18
Difference in Travel Time from Baseline (%)	11.0%
Corridor-wide Total Delay (h)	241.30
Difference in Total Delay from Baseline (%)	19.5%
Average Speed (mph)	17.23
Difference in Average Speed from Baseline (%)	-10.7%
Average Delay (s/veh)	83.99
Difference in Average Delay from Baseline (s/veh)	21.5%
Average Stop Delay (s/veh)	49.34
Difference in Average Stop Delay from Baseline (%)	15.2%
Average Driveway Delay (All Movements, s/veh)	14.76
Average Outbound Delay (s/veh)	32.14
Average Right-Out Delay (s/veh)	17.98
Average Left-Out Delay (s/veh)	45.82
Average Left-In Delay (s/veh)	44.98
Average Delay in TWLTL for Merging into Mainline (s/veh)	19.00
Average Delay in TWLTL (s/veh)	27.32

Table D.9 Case M24-RR

MOE	100 vphpd	200 vphpd
Volume Simulated	10740	11973
Difference in Volume Simulated from Baseline	11.2%	20.3%
Corridor-wide Travel Time (h)	488.98	524.45
Difference in Travel Time from Baseline (%)	10.9%	16.9%
Corridor-wide Total Delay (h)	238.37	266.17
Difference in Total Delay from Baseline (%)	18.5%	27.0%
Average Speed (mph)	17.32	16.36
Difference in Average Speed from Baseline (%)	-10.1%	-16.6%
Average Delay (s/veh)	83.29	89.28
Difference in Average Delay from Baseline (s/veh)	25.0%	37.3%
Average Stop Delay (s/veh)	44.83	43.06
Difference in Average Stop Delay from Baseline (%)	11.5%	17.2%
Average Driveway Delay (All Movements, s/veh)	1.22	1.39
Average Outbound Delay (s/veh)	18.97	21.76
Average Right-Out Delay (s/veh)	18.97	21.76

Table D.10 Case C20-M8-FA

MOE	50 vphpd	100 vphpd	C25, M150 vphpd
Volume Simulated	10268	10872	10433
Difference in Volume Simulated from Baseline	7.1%	12.3%	8.6%
Corridor-wide Travel Time (h)	458.36	488.33	471.14
Difference in Travel Time from Baseline (%)	5.0%	10.8%	7.6%
Corridor-wide Total Delay (h)	214.72	241.13	224.38
Difference in Total Delay from Baseline (%)	9.5%	19.4%	13.4%
Average Speed (mph)	18.11	16.98	17.82
Difference in Average Speed from Baseline (%)	-5.3%	-12.3%	-7.0%
Average Delay (s/veh)	76.98	83.95	79.72
Difference in Average Delay from Baseline (s/veh)	15.2%	26.5%	19.4%
Average Stop Delay (s/veh)	47.90	53.12	47.61
Difference in Average Stop Delay from Baseline (%)	13.0%	26.1%	14.2%
Average Driveway Delay (All Movements, s/veh)	61.84	73.28	19.14
Average Outbound Delay (s/veh)	89.38	107.32	44.82
Average Right-Out Delay (s/veh)	56.48	84.91	28.00
Average Left-Out Delay (s/veh)	107.86	128.22	60.40
Average Left-In Delay (s/veh)	15.81	20.45	21.22
Average Delay in TWLTL for Merging into Mainline (s/veh)	6.36	8.77	7.62
Average Delay in TWLTL (s/veh)	15.81	20.45	21.22
Average Delay for Approach Side Driveways (s/veh)	163.61	226.54	213.00
Average Delay for Departure Side Driveways (s/veh)	40.47	53.89	52.54

Table D.11 Case C20-M8-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10293	10996	11683
Difference in Volume Simulated from Baseline	7.3%	13.3%	18.4%
Corridor-wide Travel Time (h)	438.68	449.94	487.25
Difference in Travel Time from Baseline (%)	0.7%	3.2%	10.6%
Corridor-wide Total Delay (h)	195.76	203.70	231.64
Difference in Total Delay from Baseline (%)	0.8%	4.6%	16.1%
Average Speed (mph)	19.04	18.69	17.72
Difference in Average Speed from Baseline (%)	-0.1%	-2.0%	-7.6%
Average Delay (s/veh)	70.82	73.54	81.63
Difference in Average Delay from Baseline (s/veh)	8.0%	17.1%	29.7%
Average Stop Delay (s/veh)	42.02	40.12	42.09
Difference in Average Stop Delay from Baseline (%)	0.9%	2.8%	12.9%
Average Driveway Delay (All Movements, s/veh)	8.25	9.40	13.32
Average Outbound Delay (s/veh)	13.31	14.17	17.65
Average Right-Out Delay (s/veh)	13.31	14.17	17.65
Average Delay for Approach Side Driveways (s/veh)	23.62	29.67	43.45
Average Delay for Departure Side Driveways (s/veh)	5.52	5.71	7.22

Table D.12 Case C20/RR-M8/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10298	10997	11727
Difference in Volume Simulated from Baseline	7.4%	13.3%	18.7%
Corridor-wide Travel Time (h)	442.31	452.27	483.75
Difference in Travel Time from Baseline (%)	1.5%	3.7%	10.0%
Corridor-wide Total Delay (h)	199.42	205.92	230.30
Difference in Total Delay from Baseline (%)	2.6%	5.7%	15.6%
Average Speed (mph)	18.88	18.59	17.68
Difference in Average Speed from Baseline (%)	-1.0%	-2.6%	-7.9%
Average Delay (s/veh)	72.10	74.27	81.29
Difference in Average Delay from Baseline (s/veh)	9.7%	17.9%	29.7%
Average Stop Delay (s/veh)	42.66	41.25	42.62
Difference in Average Stop Delay from Baseline (%)	2.5%	5.5%	14.1%
Average Driveway Delay (All Movements, s/veh)	13.31	13.47	16.66
Average Outbound Delay (s/veh)	17.87	19.34	24.35
Average Right-Out Delay (s/veh)	9.06	11.35	14.99
Average Left-Out Delay (s/veh)	25.56	26.29	33.18
Average Left-In Delay (s/veh)	26.02	27.08	30.65
Average Delay in TWLTL for Merging into Mainline (s/veh)	9.62	10.49	11.16
Average Delay in TWLTL (s/veh)	19.83	19.88	23.66
Average Delay for Approach Side Driveways (s/veh)	28.51	28.43	37.48
Average Delay for Departure Side Driveways (s/veh)	5.85	5.90	6.29

Table D.13 Case C20-M16-FA

MOE	50 vphpd	100 vphpd	C25, M150 vphpd
Volume Simulated	10488	11295	11070
Difference in Volume Simulated from Baseline	9.0%	15.5%	13.8%
Corridor-wide Travel Time (h)	463.57	498.66	490.38
Difference in Travel Time from Baseline (%)	6.0%	12.7%	11.2%
Corridor-wide Total Delay (h)	218.79	248.96	238.43
Difference in Total Delay from Baseline (%)	11.2%	22.0%	18.5%
Average Speed (mph)	17.95	16.70	17.33
Difference in Average Speed from Baseline (%)	-6.2%	-14.2%	-10.0%
Average Delay (s/veh)	78.17	85.73	83.31
Difference in Average Delay from Baseline (s/veh)	18.2%	30.8%	27.3%
Average Stop Delay (s/veh)	48.07	52.04	47.60
Difference in Average Stop Delay from Baseline (%)	15.2%	27.3%	18.8%
Average Driveway Delay (All Movements, s/veh)	62.01	76.56	21.79
Average Outbound Delay (s/veh)	91.41	110.47	41.47
Average Right-Out Delay (s/veh)	73.50	89.74	22.39
Average Left-Out Delay (s/veh)	118.95	130.29	59.49
Average Left-In Delay (s/veh)	17.95	20.58	22.34
Average Delay in TWLTL for Merging into Mainline (s/veh)	13.15	17.36	16.27
Average Delay in TWLTL (s/veh)	17.95	20.58	22.34
Average Delay for Approach Side Driveways (s/veh)	250.61	280.72	287.47
Average Delay for Departure Side Driveways (s/veh)	54.05	91.69	116.71

Table D.14 Case C20-M16-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10516	11404	12301
Difference in Volume Simulated from Baseline	9.3%	16.4%	22.5%
Corridor-wide Travel Time (h)	447.10	460.31	494.83
Difference in Travel Time from Baseline (%)	2.6%	5.4%	12.0%
Corridor-wide Total Delay (h)	202.56	212.28	237.87
Difference in Total Delay from Baseline (%)	4.1%	8.5%	18.3%
Average Speed (mph)	18.75	18.31	17.42
Difference in Average Speed from Baseline (%)	-1.7%	-4.2%	-9.5%
Average Delay (s/veh)	73.17	76.25	83.17
Difference in Average Delay from Baseline (s/veh)	12.9%	22.9%	34.5%
Average Stop Delay (s/veh)	41.96	39.83	40.30
Difference in Average Stop Delay from Baseline (%)	2.8%	5.6%	13.4%
Average Driveway Delay (All Movements, s/veh)	9.09	10.26	13.30
Average Outbound Delay (s/veh)	13.44	14.87	21.54
Average Right-Out Delay (s/veh)	13.44	14.87	21.54
Average Delay for Approach Side Driveways (s/veh)	26.97	31.88	42.79
Average Delay for Departure Side Driveways (s/veh)	6.77	6.97	7.99

Table D.15 Case C20/RR-M16/FA

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10515	11404	12336
Difference in Volume Simulated from Baseline	9.3%	16.4%	22.7%
Corridor-wide Travel Time (h)	448.46	461.04	501.16
Difference in Travel Time from Baseline (%)	2.9%	5.5%	13.1%
Corridor-wide Total Delay (h)	204.00	213.01	243.72
Difference in Total Delay from Baseline (%)	4.8%	8.8%	20.3%
Average Speed (mph)	18.67	18.26	17.18
Difference in Average Speed from Baseline (%)	-2.2%	-4.4%	-11.0%
Average Delay (s/veh)	73.64	76.47	84.55
Difference in Average Delay from Baseline (s/veh)	13.4%	23.1%	35.7%
Average Stop Delay (s/veh)	42.76	40.67	42.27
Difference in Average Stop Delay from Baseline (%)	4.7%	7.5%	17.7%
Average Driveway Delay (All Movements, s/veh)	12.93	13.85	16.15
Average Outbound Delay (s/veh)	23.94	25.09	35.92
Average Right-Out Delay (s/veh)	14.40	15.75	24.66
Average Left-Out Delay (s/veh)	32.09	32.97	46.29
Average Left-In Delay (s/veh)	27.58	31.61	41.56
Average Delay in TWLTL for Merging into Mainline (s/veh)	13.58	16.50	16.76
Average Delay in TWLTL (s/veh)	19.75	21.86	26.24
Average Delay for Approach Side Driveways (s/veh)	28.04	29.94	39.21
Average Delay for Departure Side Driveways (s/veh)	6.17	6.50	7.28

Table D.16 Case C20-M24-FA

MOE	50 vphpd	100 vphpd
Volume Simulated	10654	11547
Difference in Volume Simulated from Baseline	10.5%	17.4%
Corridor-wide Travel Time (h)	506.42	553.69
Difference in Travel Time from Baseline (%)	14.0%	21.3%
Corridor-wide Total Delay (h)	255.68	297.53
Difference in Total Delay from Baseline (%)	24.0%	34.7%
Average Speed (mph)	16.60	15.09
Difference in Average Speed from Baseline (%)	-14.9%	-26.4%
Average Delay (s/veh)	87.17	94.68
Difference in Average Delay from Baseline (s/veh)	27.8%	38.7%
Average Stop Delay (s/veh)	53.36	59.05
Difference in Average Stop Delay from Baseline (%)	25.1%	37.8%
Average Driveway Delay (All Movements, s/veh)	86.59	95.38
Average Outbound Delay (s/veh)	129.03	139.42
Average Right-Out Delay (s/veh)	95.11	116.50
Average Left-Out Delay (s/veh)	161.61	163.41
Average Left-In Delay (s/veh)	22.65	24.11
Average Delay in TWLTL for Merging into Mainline (s/veh)	15.49	17.61
Average Delay in TWLTL (s/veh)	22.65	24.11
Average Delay for Approach Side Driveways (s/veh)	347.86	388.11
Average Delay for Departure Side Driveways (s/veh)	80.57	93.18

Table D.17 Case C20-M24-RR

MOE	50 vphpd	100 vphpd	150 vphpd
Volume Simulated	10596	11737	12885
Difference in Volume Simulated from Baseline	10.0%	18.7%	26.0%
Corridor-wide Travel Time (h)	483.38	497.88	526.78
Difference in Travel Time from Baseline (%)	9.9%	12.5%	17.3%
Corridor-wide Total Delay (h)	231.38	243.46	265.19
Difference in Total Delay from Baseline (%)	16.0%	20.2%	26.7%
Average Speed (mph)	17.51	17.11	16.42
Difference in Average Speed from Baseline (%)	-8.9%	-11.5%	-16.1%
Average Delay (s/veh)	81.56	84.49	89.09
Difference in Average Delay from Baseline (s/veh)	22.4%	32.4%	41.6%
Average Stop Delay (s/veh)	44.86	42.08	41.09
Difference in Average Stop Delay from Baseline (%)	10.1%	13.5%	19.0%
Average Driveway Delay (All Movements, s/veh)	11.50	12.44	15.28
Average Outbound Delay (s/veh)	19.33	19.84	22.57
Average Right-Out Delay (s/veh)	19.33	19.84	22.57
Average Delay for Approach Side Driveways (s/veh)	35.32	38.91	48.89
Average Delay for Departure Side Driveways (s/veh)	7.35	7.82	9.49

Table D.18 Case C20/RR-M24/FA

MOE	50 vphpd	100 vphpd
Volume Simulated	10667	11765
Difference in Volume Simulated from Baseline	10.6%	18.9%
Corridor-wide Travel Time (h)	488.92	512.27
Difference in Travel Time from Baseline (%)	10.9%	15.0%
Corridor-wide Total Delay (h)	238.88	256.99
Difference in Total Delay from Baseline (%)	18.7%	24.4%
Average Speed (mph)	17.27	16.62
Difference in Average Speed from Baseline (%)	-10.4%	-14.8%
Average Delay (s/veh)	83.42	87.44
Difference in Average Delay from Baseline (s/veh)	24.6%	34.8%
Average Stop Delay (s/veh)	46.99	45.38
Difference in Average Stop Delay from Baseline (%)	14.9%	20.0%
Average Driveway Delay (All Movements, s/veh)	18.02	23.35
Average Outbound Delay (s/veh)	35.53	39.72
Average Right-Out Delay (s/veh)	22.00	28.80
Average Left-Out Delay (s/veh)	48.61	51.34
Average Left-In Delay (s/veh)	36.54	42.02
Average Delay in TWLTL for Merging into Mainline (s/veh)	19.06	19.13
Average Delay in TWLTL (s/veh)	28.04	31.46
Average Delay for Approach Side Driveways (s/veh)	39.20	45.64
Average Delay for Departure Side Driveways (s/veh)	7.85	24.77

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