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Dynamic Traffic Modelling of the I-25/HOV Corridor

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16. Abstract

Traffic modeling is one means of being able to predict time-varying traffic conditions in an urban roadway network support traveler information systems and traffic management advisories. The development and testing of DYMOD (a dynamic traffic assignment model) was implemented in the Denver metro area to predict observed volumes and speeds during a typical weekday peak period (5am - 10am). On average, predicted flows agreed to within 12% of actual 5-minute volumes on I-25 through lanes at the detector locations. DYMOD was also able to model incident conditions to generate route diversion planning strategies during lane blocking accidents to estimate vehicle hours of delay.

Implementation:

This research is a building block for the future implementation of real-time traveler information systems that are integral components of traffic management centers to encourage alternate route diversion strategies and departure times.

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EXECUTIVE SUMMARY

This report describes a test implementation of DYMOD (a dynamic traffic assignment model) as means of predicting time-varying traffic conditions in a moderate size urban network during congested periods and incidents. The study demonstrates how one component of a future traffic management center (i.e., the dynamic traffic model) can be implemented and operated at a TMC to support traveler information systems and traffic management advisories.

Based on nonlinear optimization formulations and solution algorithms, this modelling approach had already performed well in computational tests on small networks. Thus, DYMOD was ready for validation and testing on a suitable freeway/arterial system. The I-25/HOV corridor southeast of Denver presented an excellent test environment for this application because of its (1) density of instrumentation, (2) rich diversity of highway types, and (3) dramatic variations in daily traffic conditions.

Specific objectives of this project were to:

- **Obj. A**: Develop computer databases of system characteristics (both supply and demand) for the I-25/HOV freeway/arterial corridor southeast of Denver.
- **Obj. B**: Calibrate and validate DYMOD to reproduce time-varying traffic conditions throughout this network based on historical data collected from loop detectors.
- **Obj. C**: Demonstrate the model's ability to predict volumes, speeds, and delays on alternative routes of this network during special events such as lane-blocking accidents.

A network covering about 100 square miles surrounding I-25 and I-225 southeast of Denver was developed. Hourly volume counts for roughly 20% of the network links were collected from city, county, and state traffic engineering departments throughout this area. These counts were used to estimate a morning peak-period trip matrix between 110 zones covering this area. Five-minute volume counts collected from loop detectors at on-ramps to I-25 and I-225 were used to estimate the departure times of these trips from each zone. Average speeds collected in 5-minute intervals from the through-lane detectors on I-25 were used to calibrate the model's speed-flow relationships. With these data, DYMOD was then used to predict observed volumes and speeds during a typical 5-10 AM weekday peak period. On average, predicted flows

Table 1: Summary of Estimated Accident Delays

Evaluation Measure	Case #1	Case #2	Case #3
Total Delay (vehicle hours)	742	1426	1248
Number of Directly Affected Trips	3300	6600	7200
Delay per Directly Affected Trip (mins)	13.5	13.0	10.4

Directly affected trips are the approximate number of vehicles that would have passed the accident location on I-25 during the accident in the base or "no accident" case.

agreed to within 12% of actual 5-minute volumes on I-25 through-lanes at the detector locations.

Next we modelled three lane-blocking accidents on I-25, and results indicate that DYMOD can model incident conditions so as to generate route diversion planning strategies during lane-blocking accidents and to estimate vehicle hours of delay. The full report describes the times, locations, and lane-blocking severities of these accidents as reported by Mile High Courtesy Patrol during the Fall of 1992.

Table 1 summarizes accident delays estimated by DYMOD as compared to travel times estimated by DYMOD without any accidents. Key observations are: Case #1 caused the least total hours of delay (742 hours), but the most delay per directly affected trip. Case #1 was of short duration, but caused a 50% reduction in capacity of an already narrow (3 lane) section of I-25, and happened at the very peak of rush hour. Cases #2 and #3 were of much longer duration, but caused less capacity reduction and happened mostly on the downside of the peak period. Thus, Cases #2 and #3 directly affected over twice as many trips, and caused nearly twice the total vehicle delay, but caused less delay per directly affected trip than Case #1.

The above delay estimates are conservative in that DYMOD diverts trips to alternate routes as accident queues develop. In reality, many travelers do not so readily divert from accident queues because of not having good knowledge of alternate route locations and travel times. Estimates of queuing delay assuming less route diversion were approximated for these same accidents in an evaluation study of the Mile High Courtesy Patrol. Those estimates were roughly 50% greater than the above, though still conservative in comparison to other national reports.

These results show that alternate routes bypassing these accidents could have been used more effectively by travelers had route guidance and traffic control information been utilized. The lower total delay estimates of DYMOD indicate that incident delays could be significantly reduced with travel advisory systems to guide trips around incident delays as modelled by DYMOD. Delays could be reduced even further by signal timing changes to better handle diverted flows along alternate routes in conjunction with route guidance. DYMOD can be used in a Traffic Management Center to provide this route guidance information through its ability to predict traffic flows and speeds on alternate routes as conditions develop.

Other key findings and recommendations of this project are that:

- Dynamic traffic modelling yields much closer estimates of traffic conditions than conventional transportation planning models during congested periods in urban areas (e.g., more accurate trip distance and speed information needed for route guidance and traffic impact modelling).
- Key advantages of DYMOD are that it finds a dynamic equilibrium solution rather than a simulation, and is practicable for large networks. DYMOD can be run with traffic detection input on a high-speed computer to predict evolving traffic conditions in a fraction of realtime.
- The key to successful dynamic traffic modelling is the care with which the supply and demand databases are developed. Much more detail is needed than was accepted in conventional static models.
- A geographical information system (GIS) is essential to develop the databases, and to maintain and improve them. GIS software must be enhanced, however, to display dynamic traffic volumes and speeds (observed or predicted) in a useful fashion.
- Traffic detectors (volumes, speeds, and densities) operating 24 hours a day all year round are needed at many more arterial locations than any major U.S. city has presently installed.
- Reliable incident detection data is still lacking for most freeway and arterial sections of any urban area. Intelligent or "smart" traffic management rules cannot be used with DYMOD in a TMC unless the rules are "trained" on a number of diverse accident scenarios.

This research is a building block for the future implementation of reliable traveler information systems. Traveler information systems are a basic component of many Intelligent Vehicle Highway Systems to which the Federal government has committed over $100 million in the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). The highway user is the primary long-run beneficiary of these systems. Information on traffic conditions relayed to motorists in their homes, offices,

or vehicles can greatly reduce traveler delays caused by peak-period congestion and unexpected incidents by encouraging alternative routes and departure times.

Eventually, dynamic traffic models will be integrated with traffic control centers that respond directly to realtime conditions through adjustments to arterial signals, ramp meters, and messages sent to travelers. Many design issues must be resolved to rapidly transmit voluminous traffic data to the model, analyze current conditions, and send control and guidance information back to traffic signals and motorists. Finally, wider regional coverage of traffic detectors must be a priority commitment to support the successful development and operation of dynamic route guidance and traffic control from a traffic management center.

TABLE OF CONTENTS

EXECUTIVE SUMMARY i
1. INTRODUCTION 1
1.1 RESEARCH NEED AND BENEFITS 1
1.2 RESEARCH OBJECTIVE 1
1.3. BACKGROUND 3
1.4. OVERVIEW OF PROJECT TASKS 4
2. REVIEW OF TRAFFIC ASSIGNMENT MODELS 6
2.1. STATIC TRAFFIC ASSIGNMENT 6
2.2. DYNAMIC TRAFFIC ASSIGNMENT 7
3. DESCRIPTION OF DYMOD 9
3.1. INTRODUCTION TO DYMOD 9
3.2. OVERVIEW OF BI-LEVEL PROGRAMS 10
3.3. DYNAMIC USER-EQUILIBRIUM ASSIGNMENT 11
3.4. A CONVERGENT DYNAMIC ASSIGNMENT ALGORITHM . . . 14
4. NETWORK DEVELOPMENT 17
4.1. DEFINITION OF THE STUDY AREA 17
4.2. GIS DATABASE OF SUPPLY CHARACTERISTICS 17
5. TRIP O-D AND DEPARTURE TIME ESTIMATION 20
5.1. GIS DATABASE OF DEMAND CHARACTERISTICS 20
5.2. DESCRIPTION & USE OF I-25 LOOP DETECTOR DATA 24
6. DISCUSSION OF RESULTS 25
6.1. PREDICTED VS. OBSERVED VOLUMES AND SPEEDS 25
6.2. ANALYSIS OF LANE-BLOCKING ACCIDENTS 26
6.2.1. Accident Case #1 near Colorado Boulevard 27
6.2.2. Accident Case #2 near Belleview Avenue 28
6.2.3. Accident Case #3 near Colorado Boulevard 30
6.3. SUMMARY OF ESTIMATED ACCIDENT DELAYS 31
7. SUMMARY AND CONCLUSIONS 33
LIST OF REFERENCES 36
APPENDIX A: FINAL REPORT FIGURES 39

LIST OF FIGURES

Figure 1a: S.E. Denver Network Surrounding I-25 40
Figure 1b: I-25 from Hampden Ave. to Colorado Blvd. 41
Figure 1c: I-25 from Arapahoe Rd. to Hampden Ave. 42
Figure 1d: Locations of Accidents #1 and #3 43
Figure 1e: I-25 Interchange at Evans Ave. 44
Figure 1f: I-25 Interchange at Arapahoe Rd. 45
Figure 1g: I-25 Interchange at E-470 46
Figure 1h: Typical Arterial Intersection 47
Figure 1i: Locations of I-25 On-Ramp Meters 48
Figure 1j: Typical Ramp Meter Layout on I-25 49
Figure 2a: Predicted vs. Observed I-25 Volumes 50
Figure 2b: Predicted vs. Observed I-25 Volumes 51
Figure 2c: Predicted vs. Observed I-25 Volumes 52
Figure 2d: Predicted vs. Observed I-25 Volumes 53
Figure 3a: Predicted vs. Observed I-25 Speeds 54
Figure 3b: Predicted vs. Observed I-25 Speeds 55
Figure 3c: Predicted vs. Observed I-25 Speeds 56
Figure 3d: Predicted vs. Observed I-25 Speeds 57
Figure 4a: Predicted vs. Observed Off-Ramp Volumes 58
Figure 4b: Predicted vs. Observed Off-Ramp Volumes 59
Figure 5a: Predicted vs. Observed On-Ramp Volumes 60
Figure 5b: Predicted vs. Observed On-Ramp Volumes 61
Figure 5c: Predicted vs. Observed On-Ramp Volumes 62
Figure 5d: Predicted vs. Observed On-Ramp Volumes 63
Figure 6a: Predicted Arterial Link Volumes 64
Figure 6b: Predicted Arterial Link Volumes 65
Figure 6c: Predicted Arterial Link Volumes 66
Figure 6d: Predicted Arterial Link Volumes 67
Figure 7a: Predicted I-25 Volumes (Acc. #1 vs. No Acc.) 68
Figure 7b: Predicted Alt. Rt. Volumes (Acc. #1 vs. No Acc.) 69
Figure 7c: Predicted Ramp Volumes (Acc. #1 vs. No Acc.) 70
Figure 7d: Pred. vs. Obs. I-25 Volumes (Accident #1) 71
Figure 7e: Pred. vs. Obs. On-Ramp Volumes (Accident #1) 72
Figure 7f: Pred. vs. Obs. I-25 Times (Accident #1) 73
Figure 7g: Pred. vs. Obs. I-25 Speeds (Accident #1) 74
Figure 7h: Pred. vs. Obs. I-25 Upstream Volumes (Accident #1) 75
Figure 8a: Predicted I-25 Volumes (Acc. #2 vs. No Acc.) 76
Figure 8b: Predicted Alt. Rt. Volumes (Acc. #2 vs. No Acc.) 77
Figure 8c: Predicted Ramp Volumes (Acc. #2 vs. No Acc.) 78
Figure 8d: Pred. vs. Obs. I-25 Volumes (Accident #2) 79
Figure 8e: Pred. vs. Obs. On-Ramp Volumes (Accident #2) 80
Figure 8f: Pred. vs. Obs. I-25 Times (Accident #2) 81
Figure 8g: Pred. vs. Obs. I-25 Speeds (Accident #2) 82
Figure 8h: Pred. vs. Obs. I-25 Upstream Volumes (Accident #2) 83
Figure 9a: Predicted I-25 Volumes (Acc. #3 vs. No Acc.) 84
Figure 9b: Predicted Alt. Rt. Volumes (Acc. #3 vs. No Acc.) 85
Figure 9c: Predicted Ramp Volumes (Acc. #3 vs. No Acc.) 86
Figure 9d: Pred. vs. Obs. I-25 Volumes (Accident #3) 87
Figure 9e: Pred. vs. Obs. On-Ramp Volumes (Accident #3) 88
Figure 9f: Pred. vs. Obs. I-25 Times (Accident #3) 89
Figure 9g: Pred. vs. Obs. I-25 Speeds (Accident #3) 90
Figure 9h: Pred. vs. Obs. I-25 Upstream Volumes (Accident #3) 91

Chapter One

INTRODUCTION

1.1 RESEARCH NEED AND BENEFITS

Traveler information systems will lead to more intelligently used, managed, and controlled transportation systems. Static information based on historical travel times and volume counts cannot be used to instruct travelers of current traffic conditions affected by weather, accidents, and other events. Since realtime data is unavailable for all sections of a regional freeway and arterial network, dynamic traffic models are needed to "fill in" the gaps between historical data and realtime conditions so that a traffic management center (TMC) can analyze traffic management alternatives, adjust traffic control strategies, and deliver travel guidance information.

This research is a building block for the future implementation of reliable traveler information systems. Traveler information systems are a basic component of many Intelligent Vehicle Highway Systems to which the Federal government has committed over $100 million in the Intermodal Transportation Efficiency Act of 1991. These systems have the potential to reduce peak-period congestion and improve levels of service by encouraging alternative routes and departure times, and by providing input to traffic control operations. Current information on traffic conditions relayed to motorists in their homes, offices, or vehicles can reroute travelers around congested hot spots, which reduces congestion for both users and non-users of the information.

Dynamic traffic models are not limited to realtime traffic control applications. They provide better estimates of peak-period volumes and speeds for the planning and evaluation of regional highway and transit improvements. Thus, apart from realtime operation, dynamic models can improve areawide impact assessments (e.g., congestion, pollution, and fuel consumption) of alternative TSM (transportation system management) strategies through induced shifts in trip routes, departure times, destinations, and mode choices. Though travelers are the primary beneficiaries of these systems, reductions in transportation impacts benefit non-travelers as well.

1.2 RESEARCH OBJECTIVE

The objective of this research was to implement and validate a computationally intensive (yet practicable) model (called DYMOD) of time-varying (i.e., dynamic) traffic conditions on a moderate size urban network that can be used in a TMC to support the delivery of travel guidance and traffic control information. Based on nonlinear optimization formulations and solution algorithms, this modelling approach had already performed well in computational tests on small networks. These models were ready for validation and testing on a suitable freeway/arterial system. The I-25/HOV corridor southeast of Denver presented an excellent test environment for this application because of its (1) density of instrumentation, (2) rich diversity of highway types, and (3) wide variations in daily traffic conditions.

Specific objectives of this project were to:

- **Obj. A**: Develop computer databases of system characteristics (both supply and demand) for the I-25/HOV freeway/arterial corridor southeast of Denver.
- **Obj. B**: Calibrate and validate DYMOD to reproduce time-varying traffic conditions throughout this network based on historical data collected from loop detectors.
- **Obj. C**: Demonstrate the model's ability to predict volumes, speeds, and delays on alternative routes of this network during special events such as lane-blocking accidents.

The scope of this project is limited to dynamic traffic modelling as a tool to estimate current traffic conditions by alternative routes and departure times in the I-25/HOV corridor. Beyond the scope of this project, future traffic management centers will provide realtime information on mass transit routes and times, parking availability at alternative destinations, and flight times at airports. Effects of tolls on route choice and peak-period pricing strategies to alter departure times are not directly considered here, but DYMOD can be adapted to estimate the effects of such programs.

Advanced passenger information systems are being developed to alert transit riders of current vehicle locations, estimated arrival times, and route schedules. This project did not include mode choice modelling with realtime transit information. Thus, the "return trip constraint" on mode choice expressed by a helpful reviewer of a draft proposal was not an immediate concern, but will be in later research.

Eventually, dynamic traffic models will be integrated with traffic control centers that respond directly to realtime conditions through adjustments to arterial signals, ramp meters, and messages sent to travelers. Many design issues must be resolved to

rapidly transmit voluminous traffic data to the model, analyze current conditions, and send control and guidance information back to traffic signals and motorists. The purpose of this project was to perform a successful "demonstration of concept" of how one component (i.e., the dynamic traffic model) of a future traffic management center could be implemented and operated.

1.3 BACKGROUND

A broad range of transportation research and demonstration projects are being conducted worldwide that pertain to various aspects of Intelligent Vehicle/Highway Systems (IVHS). A similar spectrum of initiatives by the European Community is called DRIVE. Examples of national and international research and demonstration projects on route guidance and driver information systems include, among others:

- Ali-Scoot in Berlin
- Autoguide in London
- ADVANCE in Chicago
- TravTek in Orlando
- PATH in California
- Guidestar in Minneapolis
- FAME (Freeway Arterial Management Effort) in Seattle
- IVHS in Michigan, with U. of Michigan claiming origin of the acronym.
- AMTICS (Advanced Mobile Traffic Info and Communication System) in Japan.

Advanced Traveler/Driver Information Systems (ATIS/ADIS) are being implemented in these cities in order to improve transportation system performance. Systems that focus specifically on assisting route choice by communicating route directions and travel times to drivers are referred to as vehicle navigation or Route Guidance Systems (RGS). Systems in which RGS information is frequently updated and relayed to area motorists in near realtime (say every 5-10 minutes) are referred to as Dynamic Route Guidance Systems (DRGS).

Many of these initiatives encompass more than route guidance and realtime travel time information. The FAME program in Seattle is focused on:

- *Freeway Management*: centralized and automated ramp metering, electronic surveillance, data collection, and HOV facility operation.

- *Freeway/Arterial Control Integration*: smart detour routing and signal timing for arterials and urban streets in response to accidents and road work on freeways.
- *Incident Management*: quickening the response to and clearance of vehicle accidents of all types from freeways and arterials involving property damage, injuries, fatalities, and hazardous spills.
- *Demand Management*: communicate information to motorists on alternative routes, modes, ridesharing, departure times, and destinations to encourage trip chaining and cooperative travel.

Each of these travel guidance systems under development and testing relies on an underlying traffic model or simplifying route guidance assumptions. However, these traffic models must be computationally practicable within reasonable computer resources. The Autoguide system in London uses simulated traffic estimates based on models SATURN and CONTRAM to forecast travel times. A traffic simulation model called KRONOS developed at the University of Minnesota provides information to the Guidestar system. Our dynamic traffic model DYMOD possesses certain theoretical and computational advantages over these other approaches.

Modelling time-varying traffic conditions throughout a regional network using detector data at specific locations enables route guidance and traffic control strategies to be analyzed. Such strategies include signal timing changes on arterials and traffic rerouting to avoid bottlenecks. With connections to realtime data retrieval (see Mahmassani & Jayakrishnan, 1991; Janson, 1991c), dynamic traffic models such as DYMOD will be used in realtime route guidance systems to inform motorists of beneficial route choices during incidents, emergencies, and special events.

1.4 OVERVIEW OF PROJECT TASKS

As stated earlier, the main purpose of this work was to evaluate the ability of DYMOD to adequately model time-varying traffic conditions on a Denver area network. The project is viewed as one step towards providing realtime traveler information and analyzing traffic control responses during incidents. Three overall objectives of the project were stated earlier. Specific project tasks were to:

1. Review research related to dynamic traffic assignment models and their applications. Use the findings of these other researchers (if applicable) to improve the modelling work of this study.
2. Develop a detailed network of southeast Denver to test the model.
    a. A transportation geographic information system (GIS) software package called TransCAD authored by Caliper Corporation was used to develop a database of network supply characteristics.

This network encompasses about a 100 square miles bordered by First Street to the north, Leetsdale and Parker Roads to the east, E-470 and C-470 to the south, and University Avenue to the west (see Figure 1a for a map of the analysis region). The two most heavily travelled roads in this area are I-25 and I-225.

b. The database of traffic supply characteristics was compiled from several sources including our own road inventory surveys and data files from the Colorado Department of Transportation (CDOT) and the Denver Regional Council of Governments (DRCOG). A major effort was to convert highway center-line GIS coordinates into a fully connected network of directional highway links and allowed turn movements at all intersections and interchanges as will be described later.

3. Estimate a morning peak-period (5-10 AM) origin-destination (O-D) trip matrix that most likely represents the real unknown one.

   a. Process three months of weekday traffic data in 5-minute time intervals at twelve counter locations monitored by CDOT for the northbound through lanes and on-ramps of each I-25 interchange to obtain average 5-minute volumes for typical weekdays.

   b. Develop a 3-stage synthetic O-D algorithm to estimate trip origins, trip destinations, and the O-D trip matrix for the 5-10 AM analysis period.

4. Implement, calibrate, and validate DYMOD to reproduce time-varying traffic conditions based on data collected from on-ramp detectors.

5. Model several known accident cases and compare with actual traffic data during those accidents to determine the ability of the model to generate alternative routing plans during lane-blocking events.

Traffic modelling research requires (1) theoretical development, (2) investigation of mathematical properties of the model and solution approach, and (3) example implementations to demonstrate these properties. Small examples are best during theoretical development, but applications to actual settings are needed to demonstrate its validity and usefulness. The major focus of this project was on model implementation, validation, and testing rather than theoretical advancement. However, several important modelling advancements were made during this project as will be described in this report. Both theoretical and computational issues concerning the mathematical formulation and solution algorithm will continue to be addressed in future work in order to improve the model and gain acceptance among practitioners and researchers.

Chapter Two

REVIEW OF TRAFFIC ASSIGNMENT MODELS

2.1 STATIC TRAFFIC ASSIGNMENT

Over the last forty years, many traffic assignment models have been developed to assist transportation planners and engineers. Travel demand forecasting originally focused on system level applications, but the emphasis changed to subarea analysis, because of the shift from capital intensive improvements to traffic management strategies. This new emphasis on subarea analysis required improved traffic assignment techniques, more detailed network representation, and improved methods of model calibration (Easa, 1991).

Traffic assignment models provide basic inputs to the planning and design of transportation facilities. Vehicular volume and speed estimates from these models are used as basic inputs to (1) highway design comparisons (e.g., capacity analyses and pavement design); (2) environmental impact analyses (e.g., air quality, energy consumption, and noise abatement); and (3) regional service analyses (e.g., travel times and delays between various parts of the region).

Historically, all urban transportation planning procedures used by metropolitan planning organizations (MPO's) to evaluate the impacts of alternative system plans have been "static" models in which the effects of time-varying travel demands are largely ignored. Static assignment models assume constant demand over time (i.e., rates of trip departures from each zone and trip arrivals to each zone are constant for the entire analysis period, although they may differ between zones).

Static assignment techniques include: (1) all-or-nothing assignment (AON), (2) deterministic equilibrium assignment, and (3) stochastic assignment (multinomial logit and multinomial probit). Equilibrium assignment techniques are widely used in practice today. Depending on the behavioral assumptions of individual route choice decisions, two possible equilibrium assignments are (1) user-equilibrium (UE) wherein users attempt to minimize individual travel costs, and (2) system-optimality (SO), wherein users cooperate in minimizing total transportation cost. The math

formulations of these two problems in the static context differ only in whether average or marginal costs are specified in the objective function.

User-equilibrium assignment is based on an underlying assumption that travelers try to minimize their own individual travel times or costs when choosing routes (Wardrop, 1952). Standard solution algorithms combine a series of all-or-nothing assignments to improve estimates of link impedances and volumes until the desired equilibrium state is sufficiently obtained as prescribed by the objective function. This method is most applicable for peak-hour assignments (Eash, Janson & Boyce, 1979; Ortuzar & Willumsen, 1990).

Valid comparisons of alternative transportation system plans or response strategies with time-varying travel demands cannot be made within the steady-state assumptions of these static models. During rapidly changing traffic conditions, a static model is no longer sufficient to explain traffic flows. Traffic conditions change quickly because of (1) varying departure rates during peak-periods, (2) arrival/departure demands at times of special events, and (3) spillback queues due to oversaturated links and intersections, often due to accidents. These traffic characteristics have motivated the study of dynamic models during the past 20 years.

2.2 DYNAMIC TRAFFIC ASSIGNMENT

Previous studies of the dynamic traffic assignment problem can be grouped into two basic approaches -- simulation or optimization. Optimization approaches include math programming formulations in discrete or continuous time with the objective being either user or system optimality. Optimization approaches include optimal control formulations in continuous time, but their implementation requires discrete time representation similar to DYMOD.

Research on dynamic network equilibrium models focused on two main concerns (Boyce, 1989). One was to develop dynamic generalizations of static UE and SO models (Yagar, 1976; Merchant & Nemhauser, 1978; Carey, 1987; Wie, 1991; Janson, 1991a). A second was to understand the effects of congestion and delay on departure time choice (Hendrickson & Kocur, 1981; Mahmassani & Herman, 1984; Ben Akiva et al., 1986). The DYMOD model applied in this study grew out of the first concern, but was later extended to address the second concern (Janson & Robles, 1993).

Early efforts to develop dynamic traffic assignment models led to heuristic simulations (e.g., Yagar, 1970; Leonard et al., 1978), where the demand is assigned to instantaneous minimum cost paths. A limitation of these earlier approaches is that they did not account for travel time changes over the entire trip duration. Leonard et

al. (1982) and Van Vliet (1982) describe simulation approaches used in CONTRAM and SATURN, respectively, to model subarea traffic schemes in greater detail including intersection movements, queuing delays, and time-varying flows. Besides the limitations of these approaches mentioned earlier, the implementation of these models is prohibitive for large networks. As reviewed by Van Aerde et al. (1987), both models are prohibitive for large networks in which links and nodes number in the tens of thousands.

The first mathematical approach to dynamic system-optimal traffic assignment was formulated by Merchant & Nemhauser (1978). Their model was formulated as a discrete time, nonlinear, and nonconvex programming program. Carey (1987) presented an extended formulation of the Merchant & Nemhauser model that is convex and nonlinear. Other researchers have since formulated the problem of dynamic SO assignment (Friesz et al., 1989) or dynamic UE assignment (Wie, 1989; Ran et al., 1993) on the basis of optimal control theory. Although these formulations have improved our theoretical understanding of how dynamic travel demands affect daily traffic flows and impedances on alternative routes, none have been implemented or solved on realistic test networks.

The dynamic traffic modelling approach applied in this project had been developed and described by the principal investigator in other research projects, presentations, and publications (see Janson 1991a, 1991b). Janson (1991a) presented a path flow formulation of the dynamic-user equilibrium assignment problem (DUE) and a heuristic solution procedure called DTA. Janson (1991b) presented a link flow formulation of DUE and a convergent solution algorithm called CDA. The entire modelling approach including combined models with trip distribution and departure time choice is called DYMOD for ease of reference, although we only apply and present results of dynamic traffic assignment in this study).

The above brief discussion of dynamic traffic assignment models is sufficient for readers interested in the application results of this project. The next chapter describes DYMOD's mathematical properties, formulation, and solution algorithm. That discussion assumes that supply and demand databases have been developed for the study area and analysis period as will be described in Chapters 4 & 5. Thus, readers can skip over this next chapter if mathematical details are of less interest.

Chapter Three

DESCRIPTION OF DYMOD

3.1 INTRODUCTION

The dynamic user-equilibrium (DUE) version of DYMOD developed and applied in this research is defined as follows:

> Given a network with speed/volume functions to predict travel times, and given a set of zone-to-zone trip tables containing the number of vehicle trips departing from each zone and headed towards each zone in successive time intervals, DYMOD finds the volume of vehicles on each link in each time interval that satisfy DUE conditions. The DUE condition to be satisfied for each pair of zones is that no path can have a lower travel time than any used path between these zones for trips departing in a given time interval.

DUE is formulated in terms of link flows as a bi-level program (see Janson & Robles, 1993; Janson, 1995). The first subproblem is solved for DUE link flows subject to non-negativity and conservation of flow constraints. When solving for the first subproblem, the "node time intervals" are held fixed to allow use of the Frank-Wolfe linear combinations method. Each node time interval is a zero-one variable indicating whether trips departing from origin zone r in time interval d reach node i in time interval t.

The second subproblem minimizes the travel time along paths used by trips departing from a zone r at a time interval d and arriving at node i at time interval t, to update the node time intervals and ensure temporally continuous trip paths. The algorithm holds the link flows calculated in the first subproblem fixed when solving for the second subproblem. The second subproblem also allows for link capacity adjustments in particular intervals due to accidents or spillback queuing effects, and satisfies first-in first-out (FIFO) requirements of trips between all zone pairs. Additional detailed descriptions of the model and example results have been presented by Janson (1991a, 1991b).

Profiles of average observed speeds were used for calibrating the parameters of the travel time versus volume impedance function used in the model. We found that

the following function fit the speed versus volume characteristics of I-25 detector data fairly well, and also matched the Highway Capacity Manual formula for intersection delay fairly closely. This function is of the general form first recommended by the Bureau of Public Roads (1964) and thus referred to as a BPR type function. However, the BPR function is often used with parameters 0.15 and 4 (instead of 0.7 and 6) because it was originally calibrated using level-of-service C capacities, which are roughly 67% to 77% of full capacities.

$$t = t_o \, [1.0 + 0.7 \, (V/C)^6]$$

where,

t = travel time to traverse the link.

t_o = free-flow travel time (units of time)

V = traffic volume (vehicles per time interval).

C = traffic capacity (vehicles per time interval).

This function is of similar shape to speed-flow relationships used in the Highway Capacity Manual (TRB, 1985) and other transportation planning and traffic engineering procedures (see Branston, 1976).

3.2 OVERVIEW OF BI-LEVEL PROGRAMS

Bi-level programs are useful formulations for problems that must satisfy two simultaneous objectives. Each objective is affected by two sets of interdependent variables, one of which is typically fixed in the evaluation of either objective. Bi-level programs differ from multicriteria programs in that there is no purposeful trade-off or weighting of competing objectives. The two objectives of a bi-level program cannot usually be combined into a single objective function because the influence of one objective versus the other may prevent the true optimal solution to the total problem from being obtained.

Bi-level programs have been applied to other network optimization problems such as network design with user-equilibrium flows (LeBlanc & Boyce, 1986). A bi-level program is of the following general form.

(UP) $\quad \underset{\mathbf{x} \in \mathbf{X}}{\text{Min or Max}} \;\; F(\mathbf{x},\mathbf{y})$

where $\mathbf{y}$ is optimal for:

(LP) $\quad \underset{\mathbf{y} \in \mathbf{Y}}{\text{Min or Max}} \;\; G(\mathbf{x},\mathbf{y})$

subject to:

$$\mathbf{H}(\mathbf{x},\mathbf{y}) \Leftrightarrow \mathbf{b}$$

all $(x,y) \geq 0$ or integer

where,

$F(x,y)$ = objective function to the upper subproblem (UP).

x = vector of decision variables in the upper subproblem (UP); x is fixed in the lower subproblem (LP).

$G(x,y)$ = objective function to the lower subproblem (LP).

y = vector of decision variables in the lower subproblem (LP); y is fixed in the upper subproblem (UP).

$H(x,y)$ = vector of constraints to both subproblems, which might be partitioned among the subproblems.

The vector of constraints $H(x,y)$ can be a mix of linear, nonlinear, or mixed-integer constraints, and can include both inequalities and equalities (denoted as <=>). Also, since y is fixed in $F(x,y)$ and x is fixed in $G(x,y)$, some constraints in $H(x,y)$ may only apply to one of the two subproblems. The DUE formulation explained next exercises all of these options.

3.3 DYNAMIC USER-EQUILIBRIUM ASSIGNMENT (DUE)

DUE can be stated equivalently in terms of path flows, but the link flow form shown here does not implicitly assume complete enumeration of all paths between zone pairs. Turn movements at each intersection are represented by separate links at each node. The exact form of each link's impedance function can be specific to the intersection or link type. The O-D trip matrix can be developed from traffic counts or from survey data and trip distribution models. In DUE stated below by equations (1-12), link lengths are computed on the basis of monotonically nondecreasing impedance functions of each link's volume in each time interval.

$$\text{(UP)} \quad \text{Minimize} \sum_{ij \in K} \sum_{t \in T} \int_0^{x_{ij}^t} f_{ij}^t(w)\, dw \tag{1}$$

subject to:

$$x_{ij}^t = \sum_{r \in Z} \sum_{d \leq t} v_{rij}^{dt} \qquad \text{for all } ij \in K,\ t \in T \tag{2}$$

$$q_{rn}^d = \sum_{t \geq d} \left[\sum_{in \in K} v_{rin}^{dt}\, \alpha_{ri}^{dt} - \sum_{nj \in K} v_{rnj}^{dt}\, \alpha_{rn}^{dt} \right] \qquad \text{for all } n \in N,\ r \in Z,\ d \in T \tag{3}$$

$$v_{rij}^{dt} \geq 0 \qquad \text{for all } r \in Z,\ ij \in K,\ d \in T,\ t \in T \tag{4}$$

where all $\{\alpha_{ri}^{dt}\}$ are optimal for:

$$\text{(LP)} \quad \text{Maximize} \sum_{s \in Z} \sum_{i \in N} \sum_{d \in T} b_{ri}^{d} \tag{5}$$

subject to:

$$\alpha_{ri}^{dt} = (0,1) \qquad \text{for all } r \in Z,\ i \in N,\ d \in T,\ t \in T \tag{6}$$

$$\sum_{t \in T} \alpha_{ri}^{dt} = 1 \qquad \text{for all } r \in Z,\ i \in N,\ d \in T \tag{7}$$

$$b_{ri}^{d} = \max\ [\ e_{ri}^{d}\ ,\ b_{ri}^{d-1} - (1.-h)\ \Delta t\ ] \qquad \text{for all } r \in Z,\ i \in N,\ d \in T \tag{8}$$

$$\{e_{rj}^{d} - \max\ [\ b_{ri}^{d}\ ,\ (t-d)\ \Delta t + \Delta f_{ij}^{tp}\ ]\}\ \alpha_{ri}^{dt} \le f_{ij}^{t}(x_{ij}^{t})\ \alpha_{ri}^{dt}$$

$$\text{for all } r \in Z,\ ij \in K,\ d \in T,\ t \in T,\ p = t\text{-}1,\ \Delta f_{ij}^{tp} = f_{ij}^{p}(x_{ij}^{p}) - f_{ij}^{t}(x_{ij}^{t}) \tag{9}$$

$$[\ b_{ri}^{d} - (t-d+1)\ \Delta t\ ]\ \alpha_{ri}^{dt} \le 0 \qquad \text{for all } r \in Z,\ i \in N,\ d \in T,\ t \in T \tag{10}$$

$$[\ b_{ri}^{d} - (t-d)\ \Delta t\ ]\ \alpha_{ri}^{dt} \ge 0 \qquad \text{for all } r \in Z,\ i \in N,\ d \in T,\ t \in T \tag{11}$$

$$b_{rr}^{d} = 0 \qquad \text{for all } r \in Z,\ d \in T \tag{12}$$

where,

N = set of all nodes.

Z = set of all zones (i.e., trip-end nodes).

K = set of all links (directed arcs).

Δt = duration of each time interval (same for all t).

T = set of all time intervals in the full analysis period (e.g., 18 ten-minute intervals for a 3-hour peak-period assignment).

x_{ij}^{t} = number of vehicle trips between all zone pairs assigned to link ij in time interval t (variable).

v_{rij}^{dt} = number of vehicle trips departing zone r in time interval d assigned to link ij in time interval t (variable).

$f_{ij}^{t}(x_{ij}^{t})$ = average travel impedance on link ij in time interval t (variable).

q_{rn}^{d} = number of vehicle trips from zone r to node n departing in time interval d via any path; zero for any node $n \notin Z$ (variable).

e_{ri}^{d} = shortest path travel time <u>less FIFO delay time at node i</u> from origin zone r to node i for trips departing in time interval d (variable).

b_{ri}^{d} = shortest path travel time from origin zone r to node i for trips departing in time interval d (variable).

α_{ri}^{dt} = zero-one variable indicating whether trips departing zone r in time interval d cross node i in interval t (henceforth called a "node time interval") (0=no;1=yes) (variable).

h = minimum fraction of time interval that trips departing zone r in time interval d+1 must follow trips departing in time interval d.

This formulation assumes a directed network G(N,K), where N is the set of nodes and K is the set of directed arcs or links. Zones (denoted by the set Z) are trip-end nodes at which trips originate and/or terminate. DUE requires nonlinear mixed-integer constraints with "node time intervals" indicating time intervals in which trips to each destination cross each node so as to insure temporally continuous trip paths. Each node time interval α_{ri}^{dt} indicates that trips departing zone r in time interval d cross node i in time interval t.

Equation (2) defines total flow on link ij in time interval t to be the sum of flows departing any zone r in any time interval $d \leq t$ using link ij in time interval t in order to formulate the objective function as given by equation (1). It is unnecessary to multiply v_{rij}^{dt} by α_{ri}^{dt} in equation (2), since trips departing origin r in the time interval d will only be assigned to link ij in time interval t allowed by whichever α_{ri}^{dt} term equals 1 in the nodal conservation of flow constraint (3). Equation (3) constrains inflow minus outflow at each node and zone in each time interval to sum to the proper trip departure totals in each time interval between each O-D pair, and equation (4) requires all link volumes to be nonnegative. In DUE, v_{rij}^{dt} is distributed uniformly over link (i,j) during each time interval t.

The upper subproblem (UP) of DUE is identical to static UE if all time interval superscripts and node time intervals are removed from equations (1-4). The lower subproblem of DUE given by equations (5-12) is not required in static UE because node-to-zone travel times $\{b_{ri}^{d}\}$ used to determine the node time intervals $\{\alpha_{ri}^{dt}\}$ are not needed to calculate steady-state link volumes. In DUE, node time intervals cannot be prespecified because they are affected by link travel times, which are affected by link loadings. Node time intervals are endogenous variables in DUE, creating nonlinear flow conservation constraints, and requiring DUE to include the lower subproblem (LP) in order to insure temporally continuous trip paths.

3.4 A CONVERGENT DYNAMIC ASSIGNMENT ALGORITHM

Whereas static UE can be solved quite efficiently by methods of linear combination for nonlinear programs with all linear constraints (e.g., Frank-Wolfe and PARTAN), these methods can easily create temporally discontinuous flows if applied directly to DUE. Instead, the two subproblems of DUE are solved successively by a convergent dynamic algorithm (CDA). CDA first solves (UP) with fixed node time intervals using the Frank-Wolfe (F-W) method of linear combinations (or similar technique), and then solves (LP) (a linear program) to update all node time intervals for the next F-W solution of (UP). The CDA algorithm terminates when fewer than an acceptable number of node time intervals change from one (LP) solution to the next. Test results presented by Janson (1991b, 1992a, 1992b) show this CDA algorithm to consistently converge to solutions that closely satisfy the necessary optimality conditions of these problems.

To clarify, the following steps are performed successively to solve subproblems (UP) and (LP) to near convergence with the CDA algorithm.

1. Input all network data, temporal trip departure matrices, and initial link flows. Initial link flows are optional, and can be set to zero, but static UE link flows reduced to the chosen time interval duration may be good starting values. Calculate initial node time intervals by solving (LP) with initial link flows. Set iteration counter n = 0.
2. Increment iteration counter n = n + 1.
3. (UP) Minimize equation (1) subject to equations (2-4), where all x_{ij}^{t} are variable and all α_{ri}^{dt} are fixed to their optimal values from (LP).
4. (LP) Maximize equation (5) subject to equations (6-12), where all α_{ri}^{dt} are variable and all x_{ij}^{t} are fixed to their optimal values from (UP).
5. Sum NDIFFS = total number of node time interval differences between iterations n-1 and n. Compare each $\{\alpha_{ri}^{dt}\}^{n}$ to $\{\alpha_{ri}^{dt}\}^{n-1}$. If NDIFFS $\leq$ small percent of all node time intervals (Z(N-1)T), then STOP. Otherwise, return to Step 2.

CDA converges toward a dynamic user-equilibrium solution for the following reasons. First, if node time intervals corresponding to the true equilibrium are known, then solving (UP) will reproduce the equilibrium link volumes from which these node time intervals can be calculated. That convergence proof follows from the fact that any set of node time intervals resulting from (LP) defines a directed network for which (UP) is a convex nonlinear program for which a global optimum exists. Second, given node time intervals that do not correspond to a true dynamic equilibrium, then solving (UP) with the F-W algorithm will produce link volumes that shift the node time intervals toward their correct values. For example, if a node time interval is too early,

then solving (UP) will assign more traffic to paths leading up to that node such that the node time interval is shifted later when recalculated in (LP). Oppositely, if a node time interval is too late, then solving (UP) will assign less traffic to paths leading up to that node such that the node time interval is shifted earlier when recalculated in (LP). Hence, CDA converges toward a set of node time intervals that when used to assign trips to the network in solving (UP) result in temporal link volumes that give rise to the same node time intervals when recalculated in (LP).

Since many bi-level programming problems are not globally convex (such as DUE, except with steady-state flows), perfect convergence is difficult to achieve. Bard (1983) describes one method of solving a linear bi-level programming problems with relatively few decision variables. Solving some bi-level programs to near convergence is less difficult in cases such as DUE where the (LP) solution tends to push the (UP) solution toward the global optimum rather than away from it. Difficulty with CDA convergence increases with the degree of DUE nonconvexity as (a) travel demands vary more greatly over time, (b) high demands load links heavily, and (c) loaded link lengths approach or exceed one time interval. An approximate rule mentioned earlier is to construct the network such that most link lengths remain less than 20% of the time interval duration.

With fixed node time intervals, subproblem (UP) is solved without fixing which links are used but only fixing the time intervals in which links are used by trips depending on their origins and departure times. Subproblem (LP) is solved with a label-setting or label-correcting shortest path algorithm adapted for temporally dependent arc lengths. Both types of shortest path algorithms will correctly find temporally continuous shortest paths given dynamic arc lengths with the restriction that vehicles do not pass each other along any link. An equivalent assumption when dealing with aggregate vehicle flows is that vehicles make only one-for-one (or zero-sum) exchanges of places in traffic along any link. This assumption is quite acceptable and even expected in aggregate traffic models.

Some cycling can occur in node time intervals between successive (LP) solutions, but such cycling can be reduced if it occurs. While perfect convergence of the CDA algorithm to optimal solutions with temporally continuous trip paths is not assured, close convergence is realized in test applications. Convergence difficulties shown to occur on small, specially configured networks are less likely to occur on larger networks where trips from many origins share common links, and such difficulties did not arise in the applications of this project. An acceptable degree of convergence was obtained in each of the example runs described later.

In addition to the southeast Denver area network described in this study, DYMOD has also been applied to several other traffic networks of realistic size and detail including:

1. Colorado Ski Country - a network of rural arterials and I-70 linking Denver and surrounding areas to all the Colorado ski resorts in this corridor. This network covers a vast region of the Rocky Mountains with over 9000 highway links and 22 origin-destination zones.
2. Chicago ADVANCE Study - a network of freeways and arterials covering an urban/suburban area northeast of Chicago. This network developed by the ADVANCE research team in their IVHS system development effort covers 400 sq. miles with nearly 20,000 highway links.
3. Pittsburgh Parkway East - a network of freeways and arterials serving commuters to Pittsburgh from the east along I-376 (the Parkway East). This network was developed in the early 80's to evaluate travel delays on alternative routes while reconstructing the Parkway East.
4. Other smaller networks representing freeway corridors with limited alternative routes to examine the effects of temporary lane blockages caused by roadwork and accidents.

A range of travel time and signal delay functions have been used in these applications. DYMOD successfully found very good solutions to each of these pproblems without convergence difficulties. These diverse applications show DYMOD to be a very flexible analysis tool, and CDA to be a robustly convergent solution algorithm for these types of dynamic traffic assignment problems.

Chapter Four

NETWORK DEVELOPMENT

4.1 DEFINITION OF THE STUDY AREA

A key consideration in defining a study area for dynamic traffic modelling is the availability of 24-hour loop detectors in the study area from which volumes, speeds, and densities can be obtained for short time intervals (less than 5 minutes). There are 12 locations on I-25 southeast of Denver at which loop detectors monitor traffic using the northbound through lanes and on-ramps of each interchange for ramp meter operation. This detector data is described later in explaining its use for O-D estimation.

4.2 DATABASE OF SUPPLY CHARACTERISTICS

A transportation Geographic Information System software package called TransCAD was used to code the network. This GIS platform proved to be very useful for displaying and analyzing the network links, as well as for editing and manipulating their attributes.

The study area network shown in Figures 1(a-j) contains 110 zones, 1714 nodes, and 3417 links. Zone centroids shown by circled dots in Figure 1b define the origin-destination (O-D) locations of trips, or trip-end locations. The 5-10 AM trip matrix represents a total of 222,218 trips, with non-zero trips between each of the (109 x 110) interzonal O-D pairs. Intrazonal trips are not modelled.

All links are unidirectional and their geographic representation is such that (1) no two links connect the same two nodes, and (2) each two-way street or highway section is represented by two oppositely directed links connecting two distinct node pairs.

All legal through or turn movements at every intersection are represented by separate links (see Figure 1h). An intersection of two 2-way streets requires at least 12 through and turn movement links connecting eight approach and exit nodes. Special lane groups and allowed U-turns require even greater intersection complexity. Thus, of the 1714 nodes and 3417 links in this network, 1395 nodes and 1778 links define

intersection turn movements. In addition, 702 links are centroid connectors usually connected to intersection approach nodes as shown in Figure 1h.

Figures 1(d-g) show the detail with which freeway interchanges are represented in the database. The study area network contains 11 interchanges on I-25 and three on I-225. Two interchanges on I-25 do not have loop detectors (University Blvd. and I-225). Three other interchanges (Colorado Blvd., Arapahoe Road, and County Line Road) have full loop detector arrangements at both northbound on-ramps.

The main advantages of representing the network with this level of detail are that (1) the delay incurred by vehicles at each through or turn movement at intersections can be estimated more accurately, and (2) illegal turn movements cannot occur in the model. On the other hand, two disadvantages of having a network too detailed are (1) the larger number of nodes and links requires more computational burden, and (2) developing the network becomes a very time-consuming task, depending on the size of the study area and the data available.

The most tedious task in converting DLG (digital line graph) files into usable form for traffic modelling is to divide every link into two oppositely directed links, and then to form all allowed turn movement connections at each intersection and interchange. This representation is critical to modelling spillback queues that form upstream of oversaturated freeway and arterial links with or without accidents present. However, there are no automated procedures or utilities to perform this task in any GIS software. We created a program to split the links and make some intersection connections, but nearly every intersection still required some reconfiguration with the GIS network drawing tools.

Since several road and intersection changes may have occurred over the year(s) since the DLG files were created, many survey trips are required to various places throughout the study area to verify the configurations of roads and intersections, numbers of lanes, turning allowances, and new roads constructed. The entire network building and conversion process for this size network required several months of full-time effort by the second author of this report.

In addition to geographic alignment coordinates, supply attributes of each link stored in the link layer of the database include:

1. ID
2. From Node
3. To Node
4. Directionality Code

5. Length
6. Link Name
7. Road Class
8. Number of Lanes
9. Capacity
10. Speed Limit
11. Free Flow Travel Time

Additional fields are available for importing data generated by any network analysis procedure, (e.g., link volumes, v/c ratios, link travel times and speeds, etc.). By comparison, the attributes of each node stored in the node layer of the GIS database, are limited to its ID, X-coordinate, and Y-coordinate.

Some of the link data (road names, lengths, speed limits, number of lanes, road classes, and GIS coordinates points) were obtained from existing CDOT databases. Discrepancies found in some of these data were corrected by checking maps and conducting field trips. Other attributes such as capacity and free flow travel time were calculated using the spreadsheet capabilities of TransCAD based on standard traffic engineering formulas such as those in the Highway Capacity Manual (TRB, 1985).

Chapter Five

TRIP O-D AND DEPARTURE TIME ESTIMATION

5.1 NETWORK DATABASE OF DEMAND CHARACTERISTICS

The next step was to decide on a sufficient number and coverage of zone centroids and their linkages to the network. Essentially, we located a zone centroid within every block subarea surrounded by signalized arterial streets, plus external centroids surrounding the region's boundaries. Each zone centroid is connected to the approach nodes of 2 to 4 intersections located on the boundaries of the zone. Each centroid connection for trips entering the network is made before traveling through the intersection, and each centroid connection for trips exiting the network is made after traveling through the intersection.

Each centroid connector was also coded with a fixed travel time equal to the approximate time needed to travel from the centroid to the network connection. Each centroid connector was also coded with an additional 6 minutes travel time to prevent trips from falsely taking short cuts through residential zones. The departure time estimates of all trips were adjusted for these six minutes. The twelve additional minutes of fixed travel time for each trip (6 minutes at each trip end) does not change the DYMOD solution in any case and was simply disregarded in assessing the results of each application run.

Our zonal areas range from less than 1/4 sq. mile in the northern denser end of the network to greater than 2 sq. miles in the southern sparser end of the network. External zones capture trips with origins or destinations several miles from the network. The process of connecting zones to the network link layer in a logical manner is also very time consuming. Traffic routing anomalies will likely appear in early executions of the model because of unexpected link usages due to zone connections. Such cases can usually be found and corrected fairly quickly with the inspection and network alteration capabilities of the GIS software.

Having defined the zone configurations, the next step is to create a peak-period trip matrix of interzonal trips for the study area. Two types of data characterize

travel demand through a network: (1) traffic flows represented by volumes at particular locations, and origin-destination (O-D) information, indicating the patterns of flows through the network. Traffic assignment is the process of allocating interzonal trips, known as O-D demands, to alternative routes serving each O-D pair. Thus, a required element for applying a traffic assignment model is a good estimate of the O-D trip table.

Obtaining an O-D trip matrix by means of surveying trip makers is highly expensive, labor intensive, prone to sampling errors, and not feasible for real-time applications. Because of these difficulties, a synthetic technique that uses traffic counts on alternative routes to estimate an O-D table can be advantageous to use.

A conventional zone-to-zone trip distribution matrix represents the number of vehicle trips that travel between each O-D pair of zones in a given analysis period. The time period represented by a trip distribution matrix used for transportation planning applications is typically 1 hour, 3 hours or 24 hours, and the trip matrix does not contain any departure or arrival time information. Whether these trips both depart and arrive within the time period, and when these trips actually travel within that period, is unknown once the trip matrix has been compiled from survey data. If the time period of a trip matrix is shortened (e.g., from one hour down to 5 minutes), then most trips departing in any given interval will not be completed within that interval. Hence, trip matrices for short time intervals represent "trip departure" matrices of trips departing from each zone and to which zone they are headed (or trips arriving at each zone and from which zone they came).

The above discussion raises a host of questions concerning the ways to estimate both O-D trips and their departure times in a combined or sequential manner. Janson & Southworth (1992) describe a method of using traffic detector data to disaggregate a peak-period trip matrix into the likely departure times of these trips. A prohibitive disadvantage of estimating departure times by O-D pair is that it requires a large coverage of 24-hour detectors reporting data every 5-minutes or so. Moreover, we did not have a peak-period trip matrix covering 5-10 AM on an average weekday to disaggregate. The Denver Regional Council of Governments (DRCOG) uses either a 24-hour or 3-hour trip matrix for most of their work. Extracting a 5-hour trip matrix for just our study area from the regional DRCOG database with very different zone configurations did not appear to be either reliable or up-to-date with current traffic patterns.

On the other hand, collecting a full range of explanatory data with which to make trip generation and attraction estimates was beyond the resources of this study

and was also likely to be error prone. Thus, despite the difficulties with O-D estimation from traffic counts, we decided it was the best strategy for developing a 5-hour trip matrix for which approximate departure times could also be estimated.

Because of spare detector coverage on this network, we decomposed the process into smaller sequential steps for which the detector coverage was more applicable. In addition to the I-25 detectors, we requested traffic count information from every state, city, or town agency in this area that we were told may have some counts. We obtained a mix of 1-hour and 24-hour counts dating back to 1990 on roughly 20% of the network links including turn movement links. As can be expected, much reconciliation and judgement was needed to pull together a set of usable peak-hour counts from this data. We then added peak-hour counts from the I-25 detector to this set.

Several methods of estimating an O-D trip matrix from traffic counts using a base trip matrix as prior information have been presented in the literature. Common approaches include generalized least squares, maximum likelihood, entropy maximization, information minimization, and Bayesian inference techniques (see Cascetta & Nguyen (1988) for a comprehensive review). Of the many O-D estimation approaches, the entropy maximizing model of Van Zuylen & Willumsen (1980) produces the most likely trip matrix from traffic counts, particularly when applied in small areas or partial networks. The model makes full use of the observed count information, and can easily incorporate a base O-D matrix as prior information to influence the outcome of the estimated matrix.

The process of O-D estimation must reconcile observed counts with link use probabilities and network flow feasibility. In our study, we repeatedly executed maximum entropy O-D estimation (with a base trip matrix and observed link counts) and static UE assignment to obtain link use probabilities that resulted in an O-D trip matrix that when assigned to the network resulted in similar link use probabilities. As a base trip matrix, we obtained an approximate pattern of peak-hour O-D trips from the Denver Regional Council of Governments, but not one that was compatible with observed counts or up-to-date with recent traffic growth. We performed the following procedure to estimate an O-D trip matrix that we could use.

1. Assign a base peak-hour trip matrix to the network with static UE assignment to obtain initial link-use proportions. Also sum these base O's and D's for use in the next step.
2. Use maximum entropy procedure to separately estimate O's & D's from traffic counts in proportion to base O's and D's from the base trip matrix using the link use proportions just obtained.

3. If newly estimated O's and D's are within a small percent change from previously estimated O's and D's (equal to the base O's and D's when this step is first executed), then STOP. Else, continue.
4. Distribute these trip ends in proportion to the base trip matrix (like an RAS updating procedure) without using a trip deterrence function because of the large proportion of pass-through trips.
5. Use static UE assignment to assign the estimated trip matrix from Step 4 to obtain a new set of link use proportions, and return to Step 2.

Since there is no assurance that the above procedure will converge, an added step prior to UE assignment in Step 5 that will "force" convergence is combine the latest trip matrix with the previously estimated matrix using the method of successive averages. We did not find this necessary in our application.

The advantage of estimating O's and D's, and then O-D trips, in separate steps is that each step requires much less computational burden than to (1) generate the entire 3-dimensional matrix of O-D link use proportions, and to (2) estimate the full O-D trip matrix from traffic counts. Also, each matrix of link use proportions by trip-end zone is much less sparse than a comparable matrix of link use proportions by O-D pair. The disadvantage of this approach is that it does not utilize O-D specific link use information. Since the F-W algorithm linearly combines successive trip assignments by origin to shortest path trees, it is unclear that this poses any disadvantage to the outcome of the above procedure.

The next step is to factor the peak-hour trip matrix up to the needed 5-hour trip matrix, and disaggregate the 5-hour trip matrix into trip departure times. Because a large percentage of total trips in this study area use I-25 for some portion of their journeys, we assumed that the entire 5-hour trip matrix could be obtained as some multiple of the estimated peak-hour trip matrix that satisfied the full 5-hour counts on I-25. The best fitting multiple was found to 3.2 for this study network. We also assumed that departure times of all trips from each origin were distributed similarly to departure times of trips using I-25 for which we had link crossing times in 5-minute intervals. Then, we traced back the link crossing times of volumes from each origin to their nearest I-25 on-ramp to approximate their probable departure times. This approach is an ad-hoc execution of the more formalized procedure defined by Janson & Southworth (1992) that appears to have worked suitably for this network.

We can combine departure time estimation with DYMOD as described by Janson & Robles (1993), but this requires knowledge of schedule delay penalties and desired arrival times of travelers by origin zone. Instead, since all origins have trips using I-25, we basically applied the Janson & Southworth approach using counter data from

I-25, and assumed similar departure time percentages from each origin for other trips that do not use I-25. As was apparent in a recent workshop on Dynamic Travel Models and O-D Estimation hosted by FHWA (FHWA, 1994), dynamic O-D and departure time estimation is operationally the "weak link" in dynamic travel modelling because of such limited coverage of available and usable count data. However, the procedure we followed for this study worked quite successfully with many hours of effort.

5.2 DESCRIPTION & USE OF I-25 LOOP DETECTOR DATA

In each northbound through lane and on-ramp lane of each interchange of I-25 are two loop detectors (see Figure 1j). The first and second loops encountered by traffic in each lane are called "primary" and "secondary" loops, respectively. This double-loop arrangement improves reliability of volume, speed, and occupancy data. The on-ramps may also have loops on the HOV lanes, loops to control ramp metering, and queue spillback detectors to prevent vehicles from backing up onto the arterial. Volume, speed, and occupancy data for every five-minute interval were archived to tape by the CDOT for each of these locations for the period June 15 to September 15, 1992. Traffic Counts

Traffic counts for these three months were used to determine the typical weekday distribution 5-minute traffic volumes for twelve on-ramps and twelve I-25 through-lane locations. These data files were recorded to computer tapes by CDOT Traffic Operations personnel at our request. These data counts consist of volume, occupancy, and speed for five-minute intervals, for the two peak periods (morning and afternoon). This study focused on the morning peak-period (5:00 AM to 10:00 AM), and only used volume and speed data for calibrating the model. Although the availability of occupancy data may have helped in calibrating the model, it was not used in this study.

A FORTRAN program was developed to extract 60 5-minute volume, speed, and occupancy averages from the data files, for each of the 24 count locations (12 on-ramps and 12 highway points). The program reads AM data for the days considered (Tuesday, Wednesday, and Thursday). It also checks the error codes in the files to decide whether to read a value, and only uses readings that lie within a prespecified range, thus, dismissing illogical or false readings. These error checks required us to develop a logical set of filtering rules.

Distributions of average weekday volumes for each link having a loop detector are shown in Figures 1(k-l) of observed average volumes for I-25 through lanes and on-ramps, respectively. The on-ramp volume profiles are very irregular because of the ramp metering operation.

Chapter Six

DISCUSSION OF RESULTS

6.1 PREDICTED VS. OBSERVED VOLUMES AND SPEEDS

In Figures 2(a-d) and 3(a-d), we compare observed and predicted volumes and speeds at all twelve northbound through links of I-25 where detectors are located just prior to the merge points of each northbound on-ramp. In Figures 4(a-b) and 5(a-d), we also compare observed and predicted volumes for six off-ramps and twelve on-ramps at these same interchanges. Detectors are not located at the off-ramps, but we computed observed off-ramp volumes by knowing the observed volumes on adjacent links.

Three features of the observed versus predicted volumes on the I-25 through lanes stand out. Agreement is very strong between observed and predicted volumes up to 7 AM for the first nine on-ramps, and up to 6:30 AM for the most northern on ramps. Differences at the three most northern on-ramps (Evans to Colorado) develop after those times as the observed volumes exceed the capacity restrictions that we use in the speed/volume functions. This 3-lane section of I-25 is coded to have a maximum capacity of 6600 vehicles per hour. However, the greatest observed volumes in Figure 2d equal 7680 vph. Thus, the model restricts volumes from rising this high, but we did not alter the capacity estimates from standard practice based on this finding. We also see that the underestimated volumes during the highest peak times show up as overestimated volumes later in the analysis period.

Comparisons of speeds correspond to the comparisons of volumes. Our predicted speeds decline much earlier than actual speeds beginning about 6:30 AM and each location. The lowest predicted and observed speeds are usually similar, but the predicted speeds tend to stay low for a much longer period of time. The model is overestimating speed reductions in most, but not all, cases. This result is satisfying in the sense that traditional static models are often criticized for grossly underestimating travel times and delays.

The predicted off-ramp volumes in Figures 4(a-b) generally agree well with observed volumes if one disregards the dramatic fluctuations in ramp volumes. The

model is not intended to show sudden fluctuations such as these. Belleview and Evans off-ramp volumes are most poorly predicted, but the observed Evans off-ramp volumes are very curious. This may be some observed data problems.

The predicted on-ramp volumes in Figures 5(a-d) generally also agree well with observed volumes. The Colorado SE cloverleaf on-ramp shows the greatest discrepancies, and appears to be an underutilized on-ramp in comparison to the adjacent NW diamond on-ramp.

Predicted volumes for other arterials in the southeast Denver area network are shown in Figures 6(a-d). Since we have no time-varying traffic counts for these links, we cannot show comparisons to observed data. However, the overall magnitudes of these predicted volumes agree with our knowledge of traffic volumes on those links.

6.2 ANALYSIS OF LANE-BLOCKING ACCIDENTS

A key advantage of DYMOD is that link-specific capacity adjustments can be input to the program to represent accident blockages, weather conditions, construction, or signal timing changes in time intervals when they occur. Capacity adjustment instructions for these events are input to DYMOD and utilized between the upper and lower problems. Capacity adjustments are not made while solving the upper problem to maintain the convexity of the upper problem's objective function.

To account for accidents or capacity-reducing events, a subroutine called QUECAP was added during this research to utilize the degree of capacity reduction on any number of links specified and the time intervals during which these reductions persisted. When capacity reductions create oversaturated conditions, speeds and magnitudes of queues spilling back onto upstream links are estimated, and capacity losses on upstream links are taken into account. These capacity losses create further upstream capacity losses and speed reductions to the extent and duration of the oversaturated condition.

This oversaturated spillback queuing adjustment is one of the most unique features of the program that other researchers have a great deal of interest in. Spillback queuing effects are quite difficult to model in any traffic model because of the severe and fluctuating conditions that take place. The two most difficult aspects of predicting spillback queuing effects are (1) the speed at which the spillback queue develops, and (2) its proportional effect of multiple inflow links to the same intersection or freeway merge section.

Lane blocking events also create an interesting problem with regard to how drivers make route choices. The two key issues are (1) when do drivers learn of the blockage, and (2) how do drivers react to this knowledge.

1. The easiest assumption to model is that drivers always select routes according to anticipated traffic conditions without any incidents.
2. The next easiest complexity is to add point-of-departure information so that drivers who learn of incidents before departing can select routes according to anticipated traffic conditions with incidents.
3. The most difficult complexity is to add in-vehicle information so that drivers who learn of incidents while driving can revise routes enroute according to anticipated traffic conditions with incidents.

DYMOD is programmed to model the first and second assumptions. To execute the third option requires several successive runs of the shortest path algorithm from each zone for departures in each time interval. Thus, trips departing from 110 zones in sixty 5-minute time intervals might require 100 x 60 x 5 = 33,000 executions of the shortest path algorithm per Frank-Wolfe iteration of the DUE upper problem rather than 6600. This level of computational burden is not prohibitive for high-speed computers, but runs would have taken too long on the DEC alpha workstation we were using. We decided that modelling the third option was beyond the scope of this project, and since in-vehicle information is fairly limited at this time, it was not needed to represent current traffic conditions and responses to accident scenarios.

In examining the results presented next, it is important to remember that DYMOD represents conditions where travelers have good knowledge of alternate routes as would be provided by an information system. In DYMOD, travelers readily divert to alternate routes. In reality, travelers are observed to stay more persistently in accident queues because of not having good knowledge of alternate route availability and travel times. As a result, DYMOD shows less far upstream effects of backspill queuing ahead of accidents, since these trips divert to alternate routes earlier in their trip paths. Total vehicle delays estimated by DYMOD and discussed at the end of this chapter tend to be conservatively low. Comparisons to delay estimates assuming less route diversion thus reflect the potential range of delay reduction via route guidance implementation.

6.2.1 Accident Case #1 near Colorado Boulevard

Figure 1d shows the location of an accident that occurred on September 21, 1992. According to the Mile High Courtesy Patrol (a CDOT sponsored motorist assistance service), the accident occurred at about 7:15 AM and was cleared about 7:40 AM. It was reported to be occupying the right lane, which caused roughly 50% of this 3-lane

section's capacity to be lost for that period of time. Figure 7a compares predicted traffic volumes through this section of I-25 with and without the accident (Acc versus NoAcc).

Figure 7b shows the tremendous increase in traffic exiting I-25 at Evans and using the Frontage Road to re-enter I-25 at the Colorado_NW on-ramp. (The NW on-ramp serves traffic approaching I-25 from the north, while the SE on-ramp serves traffic approaching I-25 from the south.) A small portion of diverted traffic traveled west on Evans, and then north on Colorado Blvd. to re-enter I-25 at the Colorado_SE on-ramp. These respective on-ramp volume increases are shown in Figure 7c. Also shown is that traffic is prevented from using the Colorado Blvd. off-ramp, thus increasing the severity of the queue.

The real comparison is to actual traffic volumes and speeds on that day. Figure 7d shows the comparison of predicted to observed I-25 volumes on the day of the accident for which we see a fairly close agreement. The comparison of predicted to observed on-ramp volumes in Figure 7e shows that greatly fluctuating ramp volumes during an accident are more difficult to predict. Figures 7(f-g) show fairly good predictions of travel times and speeds on I-25 during the accident, except for the sharp spike in travel time at Evans just as the accident was being cleared. In the accident description file, we did not specify to DYMOD that a momentary but more severe capacity loss might occur just as the accident was being cleared.

Upstream effects are most difficult to completely capture in DYMOD in which drivers have much greater knowledge of alternative routes than in reality, and thus divert more readily to these routes. However, Figure 7h shows that accident impacts on traffic volumes were partly captured by the model as far back as 4 miles upstream of the accident at Belleview Avenue.

A traffic control observation is that traffic delays upstream of this accident could be lessened by two actions. First, signal timing changes or coordination by patrol officers could be quickly implemented to ease delays on traffic exiting I-25 at Evans and using either the Frontage Road or westbound Evans. Next, advance information to motorists of the accident queue forming could divert more travelers at Hampden and Yale prior to getting caught in the accident queue.

6.2.2 Accident Case #2 near Belleview Avenue

Figure 1e shows the locations of two accidents that occurred on October 20, 1992. According to the Mile High Courtesy Patrol, the first accident occurred near Hampden Avenue at about 7:10 AM and was cleared about 7:30 AM. It was reported to be

occupying the right shoulder and part of the right lane, which caused roughly 30% of this 4-lane section's capacity to be lost for that period of time.

The second accident occurred near Belleview Avenue at about 7:15 AM and was cleared about 8:25 AM. It was reported to be occupying the right lane and part of the adjacent lane, which means that about 50% of this 4-lane section's capacity was lost for that period of time.

Figure 8a compares predicted traffic volumes through this section of I-25 with and without the accident (Acc versus NoAcc). Figure 8b shows the increase in traffic exiting I-25 at Orchard and traveling east or west on Orchard to alternative routes to re-enter I-25 via I-225 or at Hampden. Figure 8c shows decreases in traffic entering I-25 at Belleview and Orchard, but an increase in traffic entering I-225 at Tamarac and then onto I-25 from there.

Figure 8d shows the comparison of predicted I-25 volumes to observed I-25 volumes on the day of the accident. We observe a very close agreement at the Belleview and Orchard detectors, but not at the Hampden detector. We underestimated the capacity loss and traffic impacts due to the first accident at Hampden. Observed volumes rise up to the predicted volumes when the first accident is cleared, but drop off sharply again due to the second accident. DYMOD shows high traffic volumes at Hampden during the second accident because DYMOD rerouted traffic back onto I-25 via the Belleview on-ramp (which was beyond the accident) and via I-225. Both of these alternate routes could have been used effectively to avoid the accident queue by many travelers if they had known the location of the accident via some type of information system. We think that travelers diverted from I-25 at Orchard did not attempt to re-enter I-25 until much further north if at all, or simply waited in the queue on I-25. Significant delays could have been reduced by alerting travelers to these routes and altering the signal timing along these routes to better handle the diverted flows.

The comparison of predicted to observed on-ramp volumes in Figure 8e shows the difficulty of predicting quickly changing on-ramp volumes during an accident. Figures 8(f-g) show very good predictions of travel times and speeds on I-25 during the accident. Oddly, the impacts on travel times and speeds at Hampden are overpredicted when volume impacts there were underpredicted. On the other hand, travel times and speeds at Hampden are predicted fairly well during the second accident when volumes there were underpredicted.

In contrast to Case #1, Figure 8h shows that upstream effects on traffic volumes were captured very well by DYMOD as far back as 3-4 miles upstream of the accident

at Dry Creek. Part of the reason why greater upstream effects are captured by the model is that alternate routes around this accident location are not as readily accessible as they are around the Case #1 location.

6.2.3 Accident Case #3 near Colorado Boulevard

Figure 1d shows the location of three accidents that occurred on December 7, 1992. According to the Mile High Courtesy Patrol, a disabled vehicle stopped on the road near Colorado Blvd. at about 7:10 AM, but was quickly cleared or restarted and driven away by 7:20 AM. For this brief duration, it was reported to be occupying the right shoulder and part of the right lane, which caused roughly 30% of this 3-lane section's capacity to be lost for that time.

A second accident occurred near Colorado Boulevard at about 7:35 AM and was cleared about 8:00 AM. It was reported to be occupying the right lane and causing about 40% of this 3-lane section's capacity to be lost for that period of time. A third accident occurred near Colorado Boulevard at about 7:50 AM and was cleared about 8:40 AM. It was reported to be mostly in the right shoulder and causing roughly 20% of this 3-lane section's capacity to be lost for that period of time. Of interest here is that these later two accidents overlapped in time. Thus, traffic flow disruptions caused by the second accident were compounded by the third accident, thus making the entire accident scenario quite complex.

Figure 9a compares predicted traffic volumes through this section of I-25 with and without the accident (Acc versus NoAcc). Figure 9b shows the tremendous increase in traffic exiting I-25 at Evans and using the Frontage Road to re-enter I-25 at Colorado_NW on-ramp. A smaller portion of the diverted traffic traveled west on Evans, and then north on Colorado Blvd. to re-enter I-25 at Colorado_SE on-ramp. These respective on-ramp volume increases are shown in Figure 9c. Also shown is that traffic is prevented from using the Colorado off-ramp, thus increasing the severity of the queue.

Figure 9d shows the comparison of predicted to observed I-25 volumes on the day of the accident to be in fairly close agreement. The comparison of predicted to observed on-ramp volumes in Figure 9e is similar to Figure 7e for accident case #1, except that the model overpredicts the amount of diverted traffic to re-enter I-25 at the Colorado_NW ramp. Figures 9(f-g) show fairly good predictions of travel times and speeds on I-25 during the accident, except for the sharp spikes in travel time at Evans just as each accident was being cleared due to the momentary but severe capacity loss that occurs just as each accident is being cleared.

Table 6-1: Summary of Estimated Accident Delays

Evaluation Measure	Case #1	Case #2	Case #3
Total Delay (vehicle hours)	742	1426	1248
Number of Directly Affected Trips	3300	6600	7200
Delay per Directly Affected Trip (mins)	13.5	13.0	10.4

Directly affected trips are the approximate number of vehicles that would have passed the accident location on I-25 during the accident in the base or "no accident" case.

Upstream effects as far back as Hampden can definitely be seen in Figure 9h, but upstream effects as far back as Belleview were not well captured by the model in this case. The same traffic control options suggested for accident case #1 apply here. Signal timing changes or manual traffic control could be quickly implemented to ease delays on traffic exiting I-25 at Evans and using either the Frontage Road or westbound Evans. Providing motorists headed toward the accident location with earlier warnings and route guidance could divert more travelers at Hampden and Yale prior to getting caught in the accident queue.

6.3 SUMMARY OF ESTIMATED ACCIDENT DELAYS

A major motivation for developing advanced route guidance and traffic control systems is to reduce vehicle delays. Achieving this goal can reduce wasted hours of potentially productive person hours and speed the delivery of needed goods and services. Many scheduled activities and modern production systems depend on the timely arrival of persons and goods needed for these operations.

Beyond the loss of time, however, many other transportation impacts are directly related to vehicle hours of delay. Obviously, greater hours of engine running time increase fuel consumption and pollution emissions, and more so do to less efficient engine combustion at slower operating speeds. But disrupted traffic flows, particularly unexpected ones, also lead to greater numbers of accidents. And if not accidents, at least greater wear-and-tear on travelers and their vehicles.

Table 6-1 summarizes delays caused by the three accident cases as estimated by DYMOD in comparison to the base case without any accidents. Case #1 caused the least total hours of delay (742 hours), but the most delay per directly affected trip.

Case #1 was of short duration, but it caused a 50% reduction in capacity of an already narrow (3 lane) section of I-25, and it happened at the very peak of rush hour. Case #2 was of much longer duration, but caused only a 40% reduction in capacity of a wider 4-lane section of I-25, and it happened mostly on the downside of the peak period. Thus, Case #2 directly affected twice as many trips, and caused nearly twice the total vehicle delay, but caused slightly less delay per directly affected trip than Case #1.

Case #3 was also quite long, but never so severe as Case #1 in terms of lane closure, and also happened mostly on the downside of the peak period. Thus, while it directly affected more trips than either Case #1 or #2, Case #3 caused less total delay than Case #2, and the least delay per directly affected trip of all the cases. While delay per directly affected trip provides a comparison of incident duration and severity, total impact is the ultimate concern.

The above delay estimates are conservative in that they represent best conditions with no intervention to make signal timing or ramp metering adjustments as queues develop. DYMOD by design diverts travelers to alternate routes, whereas travelers are observed to not so readily divert from the accident queue because of not having good knowledge of alternate route locations and travel times. Estimates of queuing delay assuming less route diversion were approximated for these same accidents in an evaluation study of the Mile High Courtesy Patrol (Cuciti et al., 1993). Those estimates were roughly 50% greater than the above, though still conservative in comparison to other national reports. In that DYMOD represents route diversions with alternate route information, these results indicate that incident delays can be significantly reduced with travel advisory systems.

Chapter Seven

SUMMARY AND CONCLUSIONS

This report presented the results of testing the dynamic traffic assignment model called DYMOD as means of predicting realtime traffic flows for traveler information systems and traffic management. A primary objective of this effort was to determine whether DYMOD could adequately predict volumes and vehicle delays on alternative routes during congestion causing incidents.

A network covering about 100 square miles surrounding I-25 and I-225 southeast of Denver was developed. Hourly volume counts for roughly 20% of the network links were collected from city, county, and state traffic engineering departments throughout this area. These counts were used to estimate a morning peak-period trip matrix between 110 zones covering this area. Five-minute volume counts collected from loop detectors at on-ramps to I-25 and I-225 were used to estimate the departure times of these trips from each zone. Average speeds collected in 5-minute intervals from the through-lane detectors on I-25 were used to calibrate the model's speed-flow relationships. With these data, DYMOD was then used to predict observed volumes and speeds during a typical 5-10 AM weekday peak period. On average, predicted flows agreed to within 12% of actual 5-minute volumes on I-25 through-lanes at the detector locations.

Next we modelled three lane-blocking accidents on I-25, and results indicate that DYMOD can be used to generate route diversion planning strategies during lane-blocking incidents and to estimate vehicle hours of delay. Results indicated that incident delays could be significantly reduced with travel advisory systems to guide trips around incident delays. Delays could be reduced further by signal timing changes to better handle diverted flows along alternate routes in conjunction with route guidance. DYMOD can be used in a Traffic Management Center to provide this route guidance information through its ability to predict traffic flows and speeds on alternate routes as conditions develop.

DYMOD can also be used to perform "off-line" analyses of various lane-blocking scenarios for preplanning purposes. Such exercises can be run to develop a set of

proactive response plans for accidents at critical locations in the network. Such exercises can also be run for work zone traffic management design, analysis of detour routing schemes, preparation a predicted storm, or preparation for a major spectator event.

Several general recommendations can be concluded from this project:

- Dynamic traffic modelling yields much closer estimates of traffic conditions than conventional transportation planning models when applied to urban area networks during congested periods.
- Dynamic traffic modelling of the DYMOD approach is practicable for reasonably large urban area networks. It can be run concurrently with traffic detection input on a high-speed computer to provide updated traffic management information in a fraction of realtime.
- Dynamic traffic models can be combined with microsimulation models of smaller network subareas to achieve more accurate traffic flows for detailed traffic control adjustments. Alternatively, dynamic traffic models themselves applied to specific subareas of a network such as only I-25 produces closer estimates of traffic conditions as we demonstrated in the earlier work of this project and presented in a working paper.
- The key to successful dynamic traffic modelling is the care with which the supply and demand databases are developed. Much more detail is needed than was accepted in conventional static models.
- A geographical information system (GIS) is absolutely needed to initially develop the databases, and to continue to correct and improve them. A major need here is that utilities be developed to convert digital line graph (DLG) files of highway center-line coordinates into unidirectional links with proper intersection turn movement connections.
- Traffic detectors (volumes, speeds, and densities) operating 24 hours each day all year round are needed at many more arterial locations than any major U.S. city has installed. GIS software must, however, be enhanced to display dynamic traffic volumes and speeds (observed or predicted) in a useful fashion.
- Finally, reliable incident detection data is still lacking for most freeway and arterial sections of any urban area. DYMOD or any realtime modelling approach cannot respond to accidents with traveler information or traffic control adjustments unless it is given accurate information about the accident time, location, and severity. Also, intelligent or "smart" traffic management rules cannot be developed for use with DYMOD in a traffic management center unless the program is refined or "trained" on a number of diverse accident scenarios for testing.

Thus, wider regional coverage of traffic monitoring and detection must be a priority commitment to support the successful development and operation of dynamic

route guidance and traffic control from a traffic management center. Since the above results indicate that incident delays can be significantly reduced with travel advisory systems, the investment into further research and development appears well justified.

Eventually, dynamic traffic models will be integrated with traffic control centers that respond directly to realtime conditions through adjustments to arterial signals, ramp meters, and messages sent to travelers. Many design issues must be resolved to rapidly transmit voluminous traffic data to the model, analyze current conditions, and send control and guidance information back to traffic signals and motorists. The purpose of this project was to perform a successful "demonstration of concept" of how one component (i.e., the dynamic traffic model) of a future traffic management center could be implemented and operated.

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Appendix A: Final Report Figures

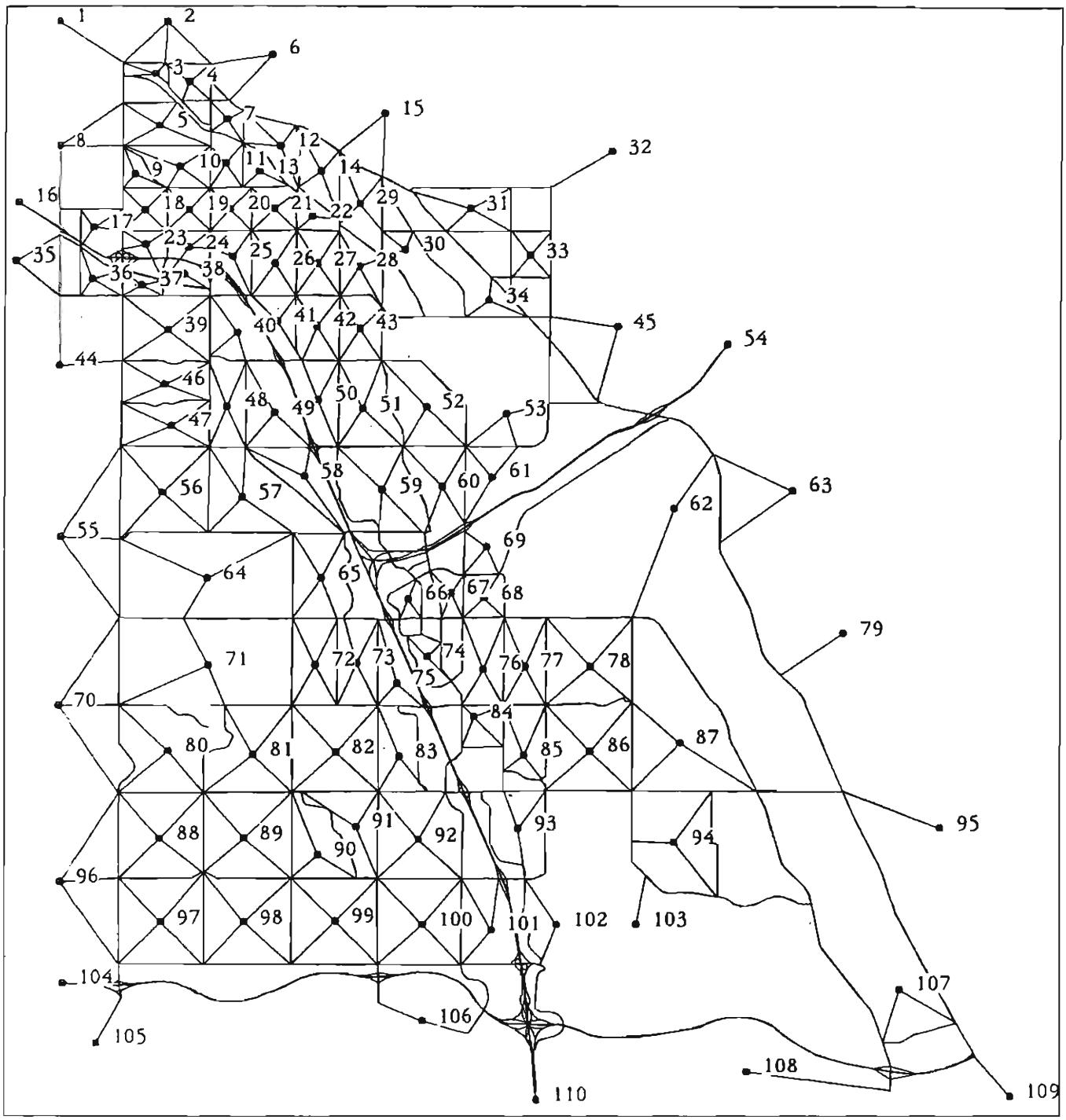

Figure 1a: S.E. Denver Network Surrounding I-25

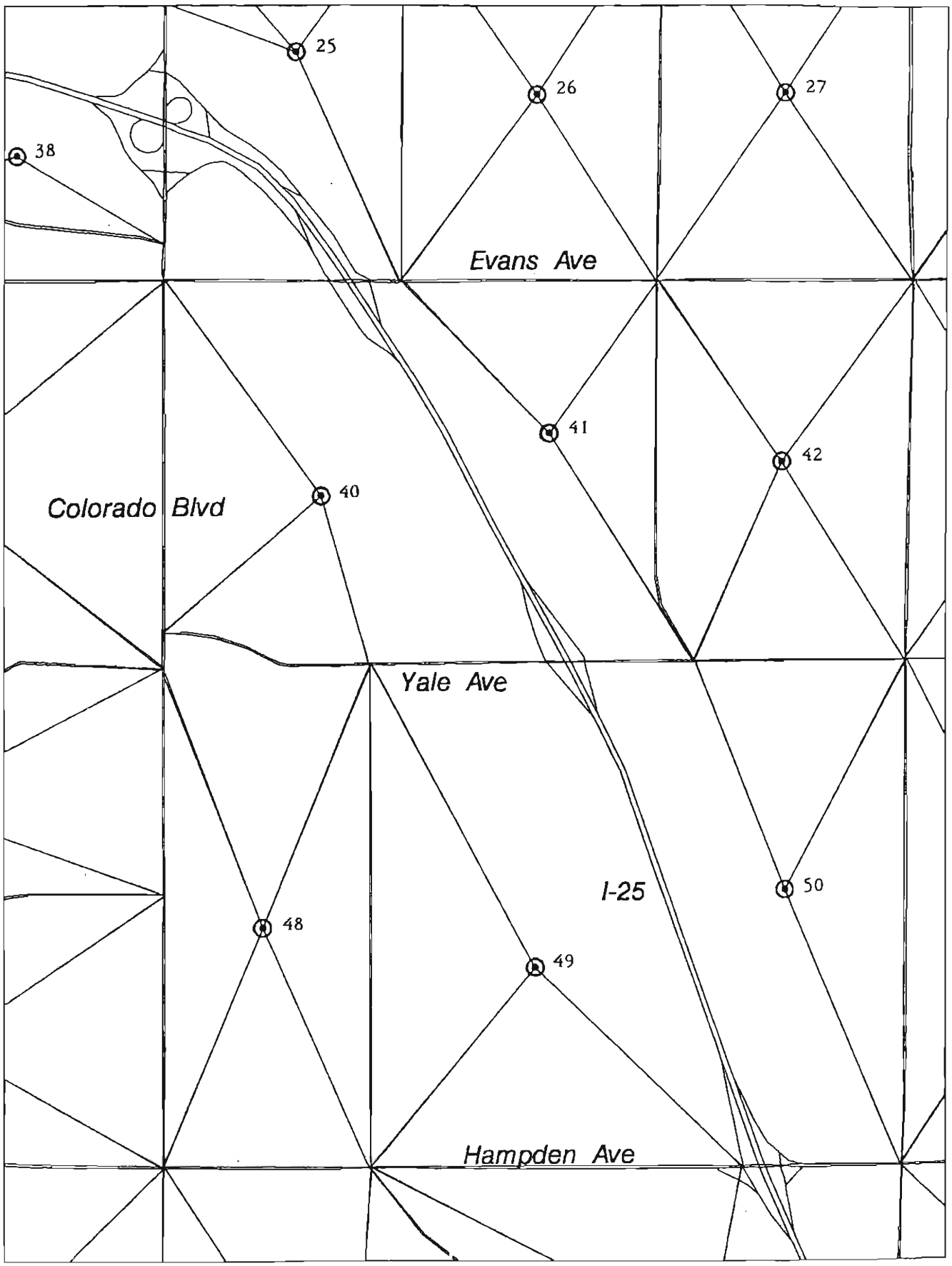

Figure 1b: I-25 from Hampden Ave. to Colorado Blvd.

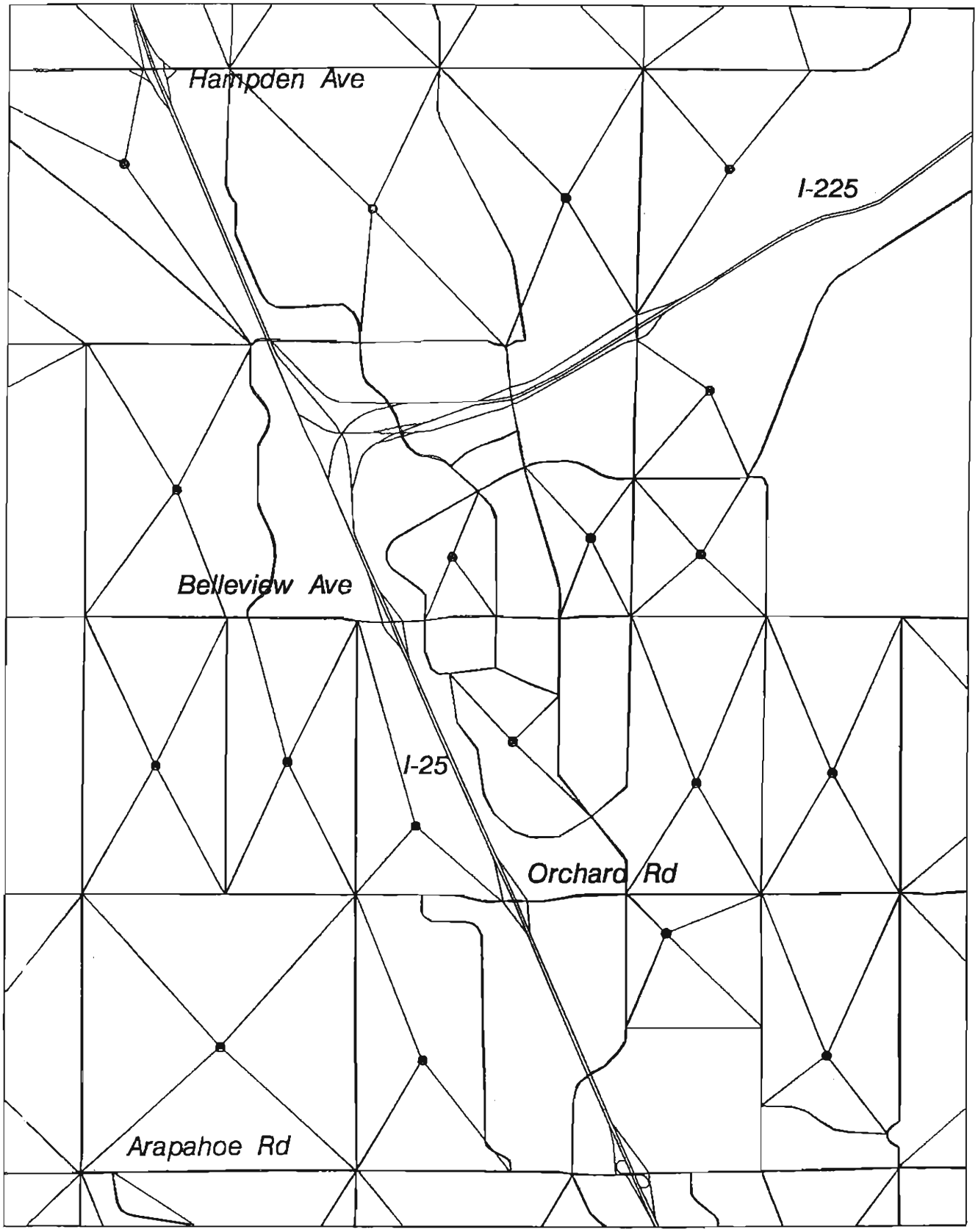

Figure 1c: I-25 from Arapahoe Rd. to Hampden Ave

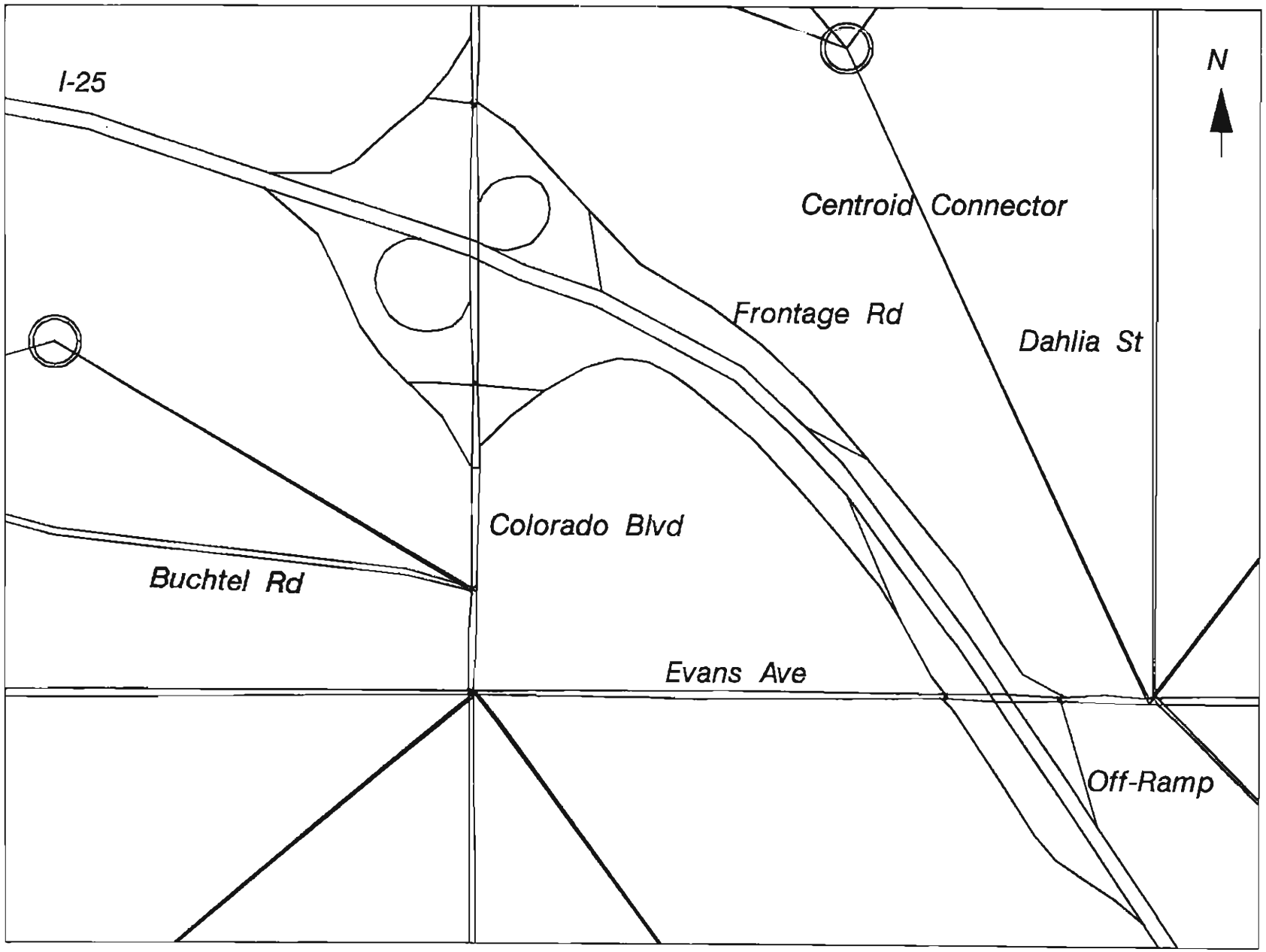

Figure 1d: Locations of Accidents # 1 and # 3

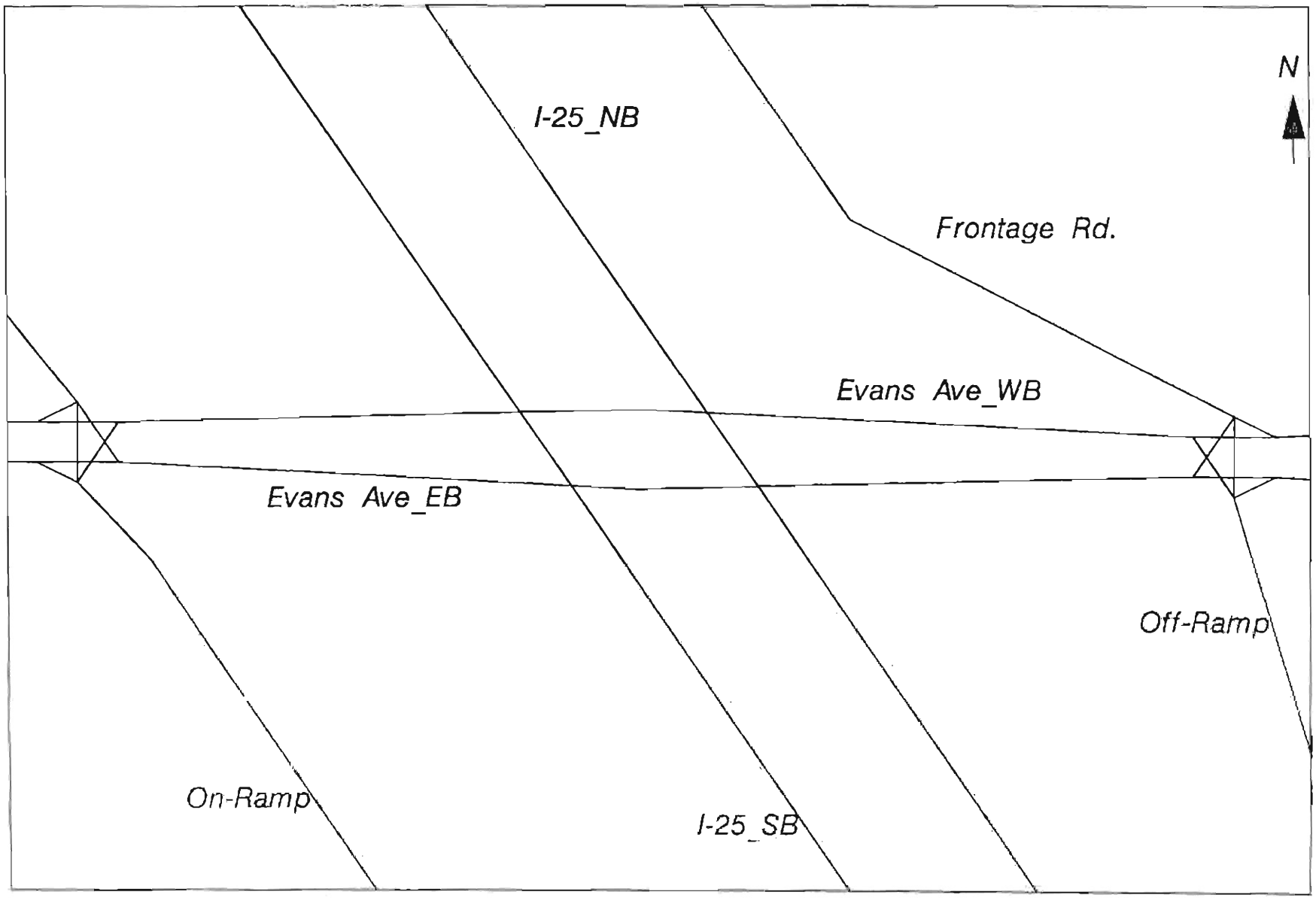

Figure 1e: I-25 Interchange at Evans Ave.

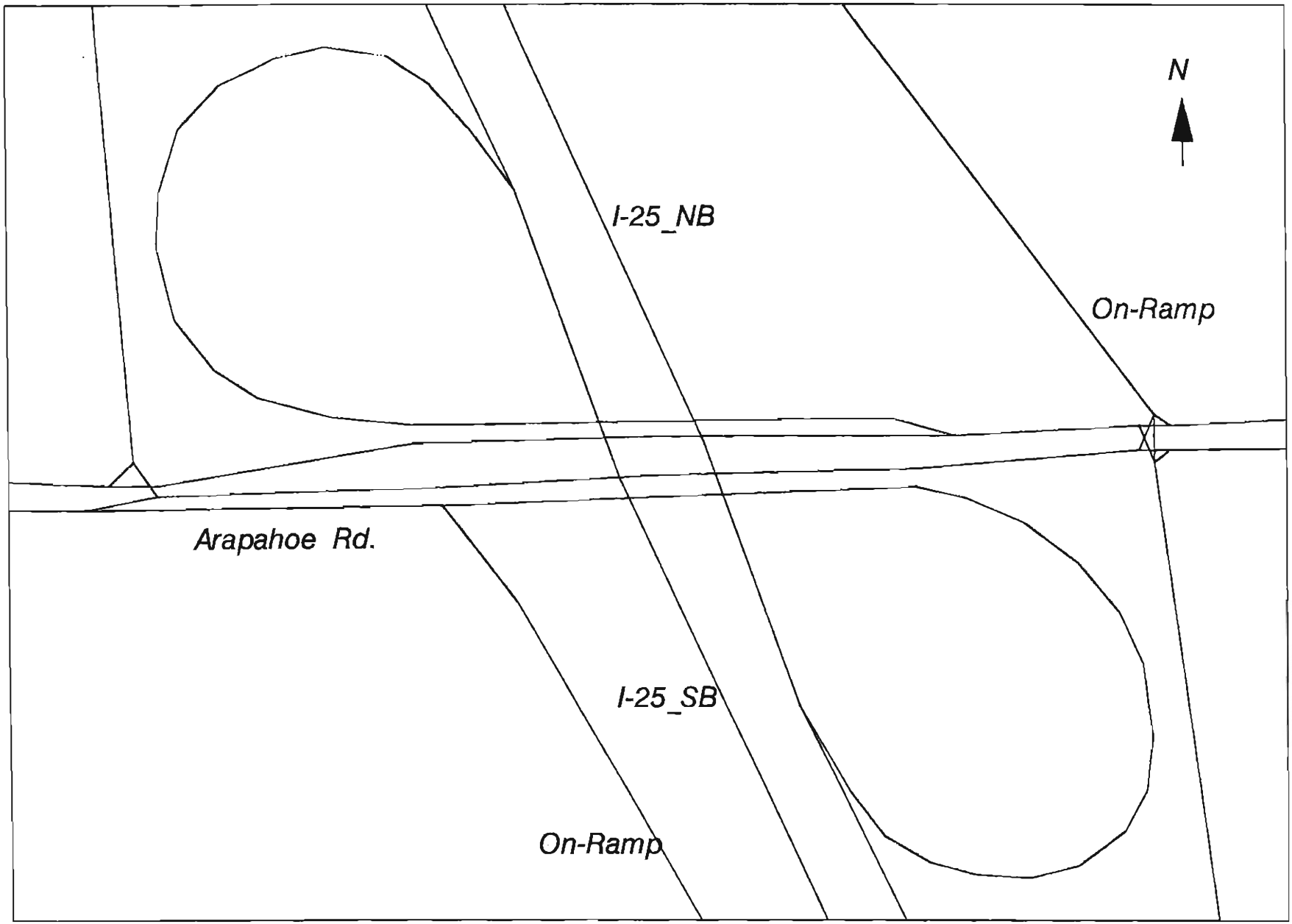

Figure 1f: I-25 Interchange at Arapahoe Rd.

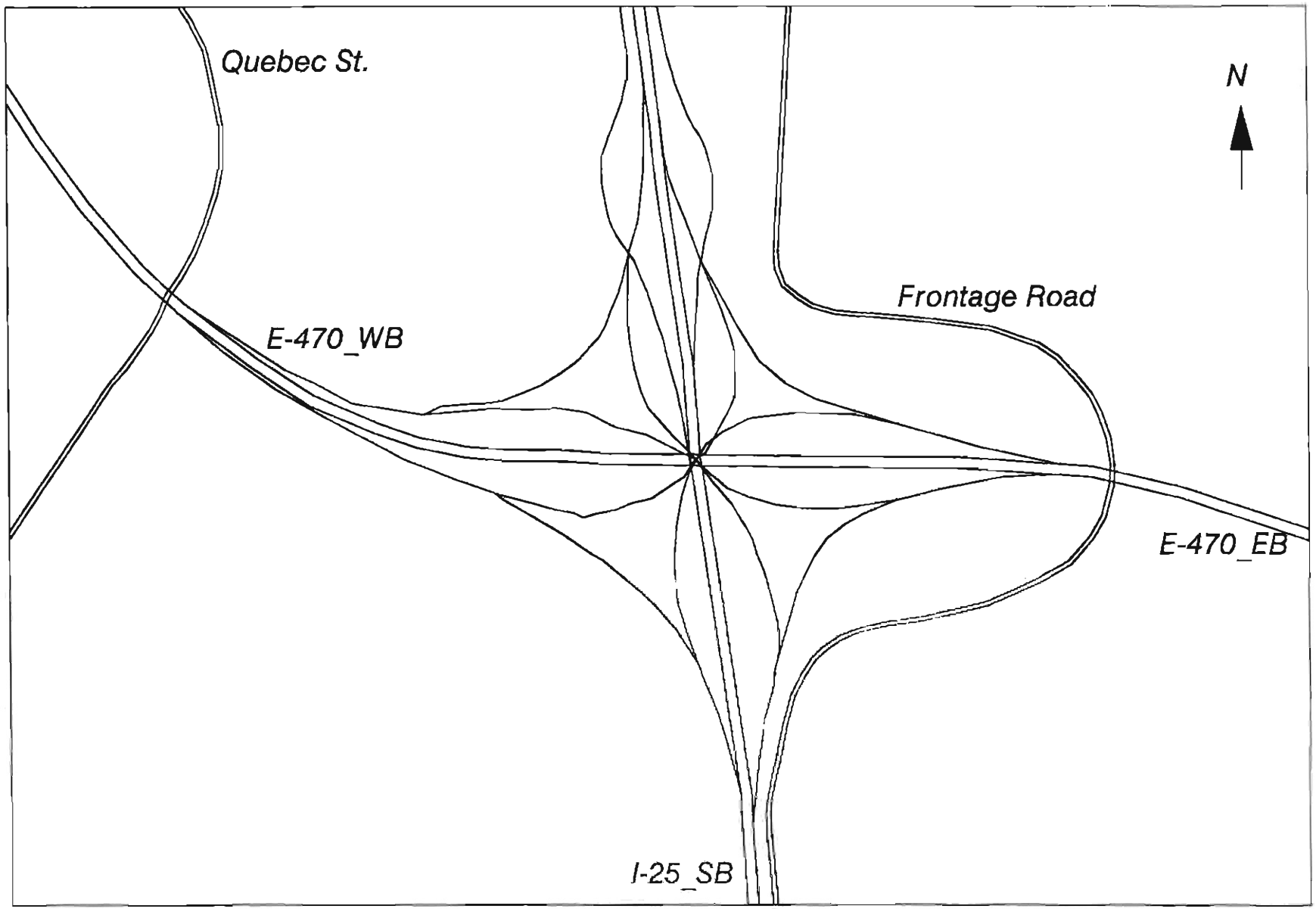

Figure 1g: I-25 Interchange at E-470

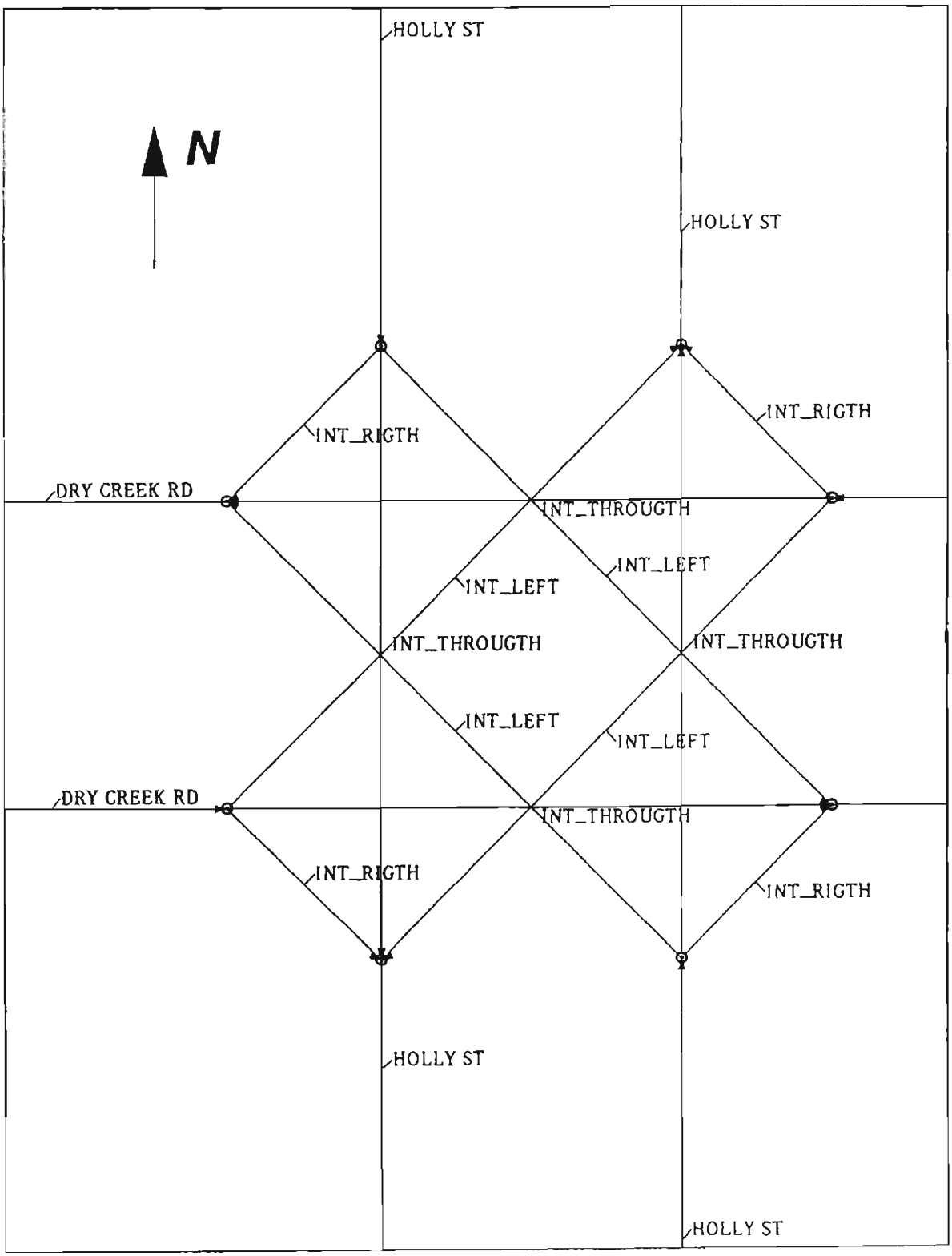

Figure 1h: Typical Arterial Intersection

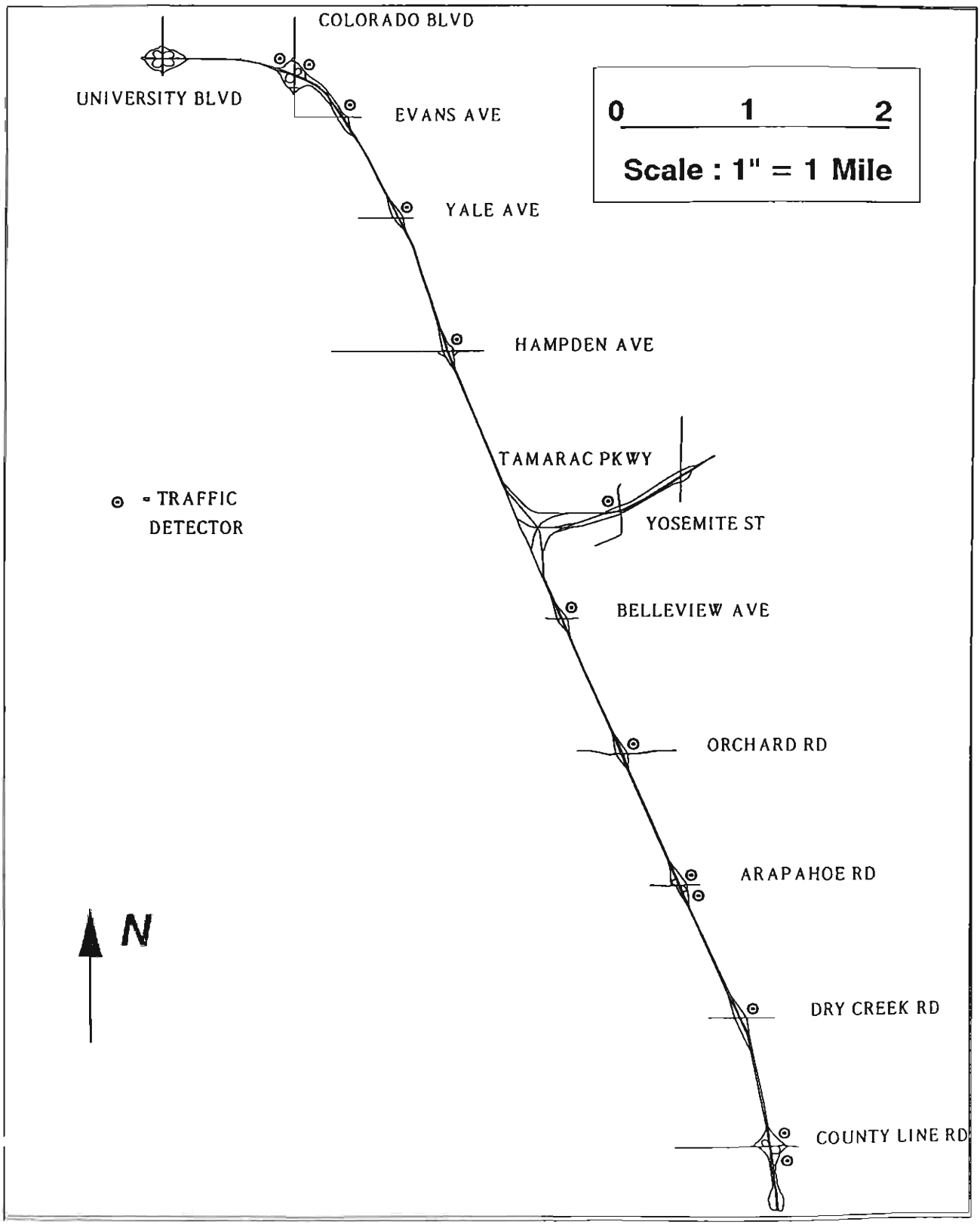

Figure 1i: Locations of I-25 On-Ramp Meters

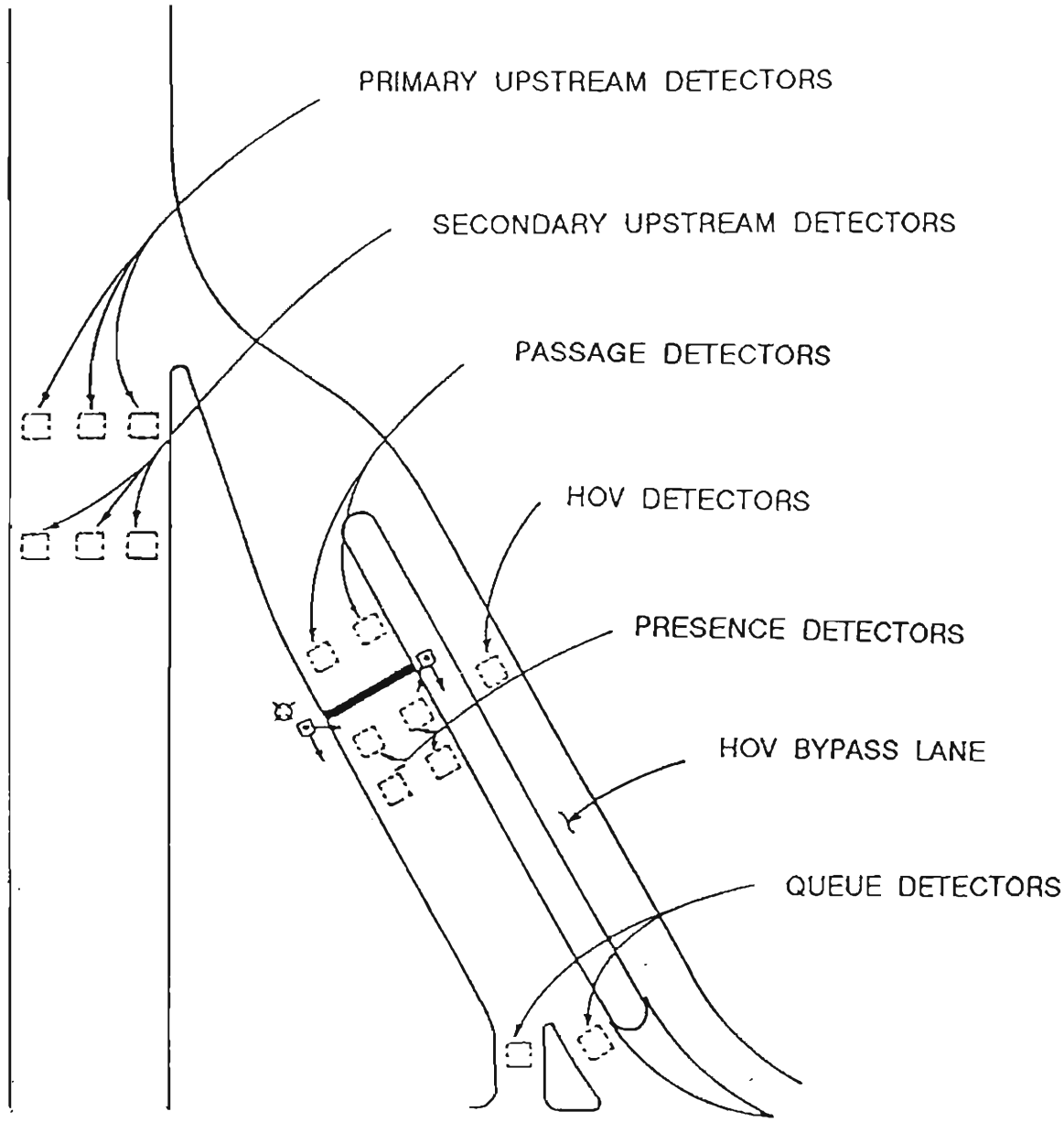

Figure 1j: Typical Ramp Meter Layout on I-25

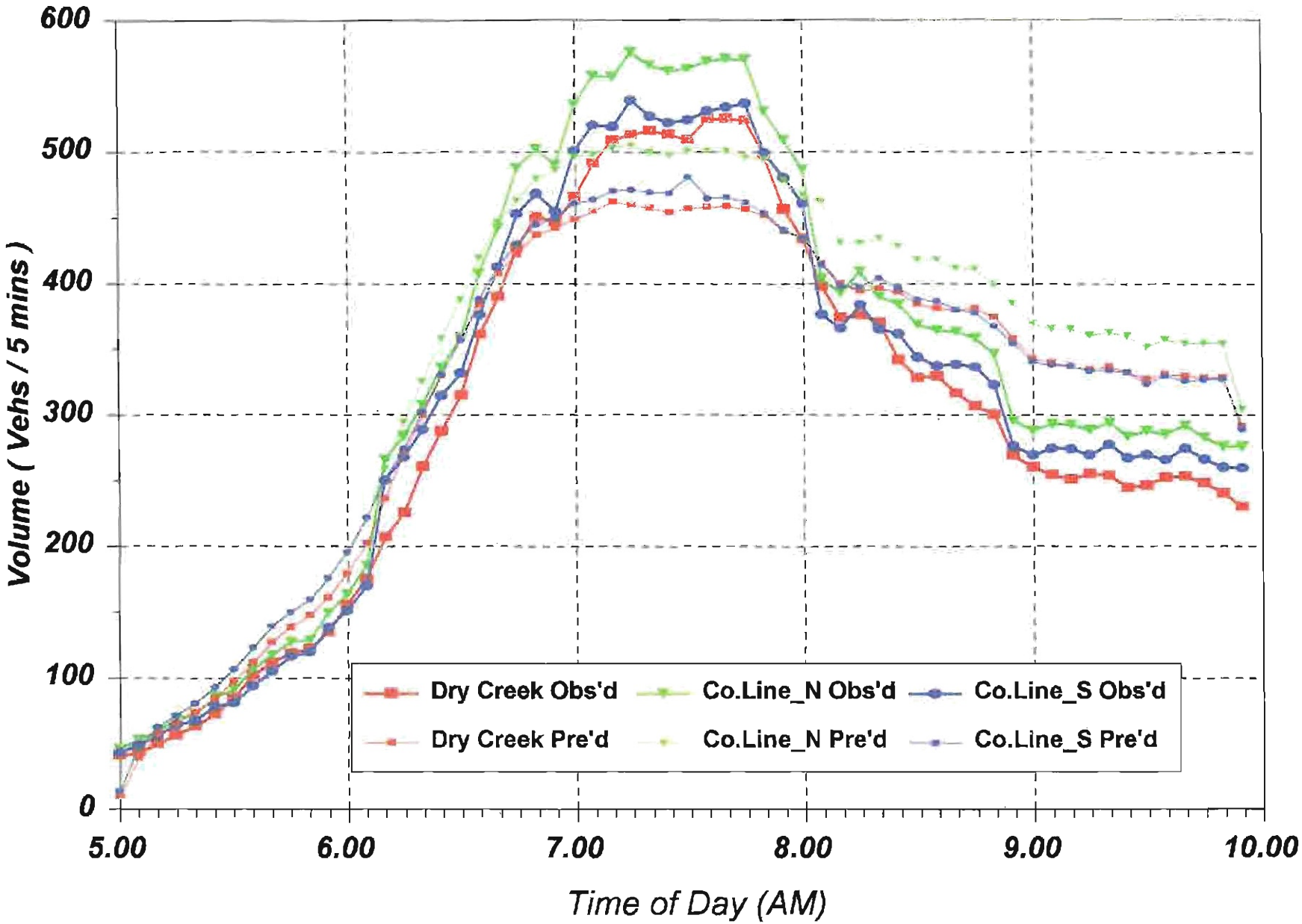

Figure 2a: Predicted vs. Observed I-25 Volumes

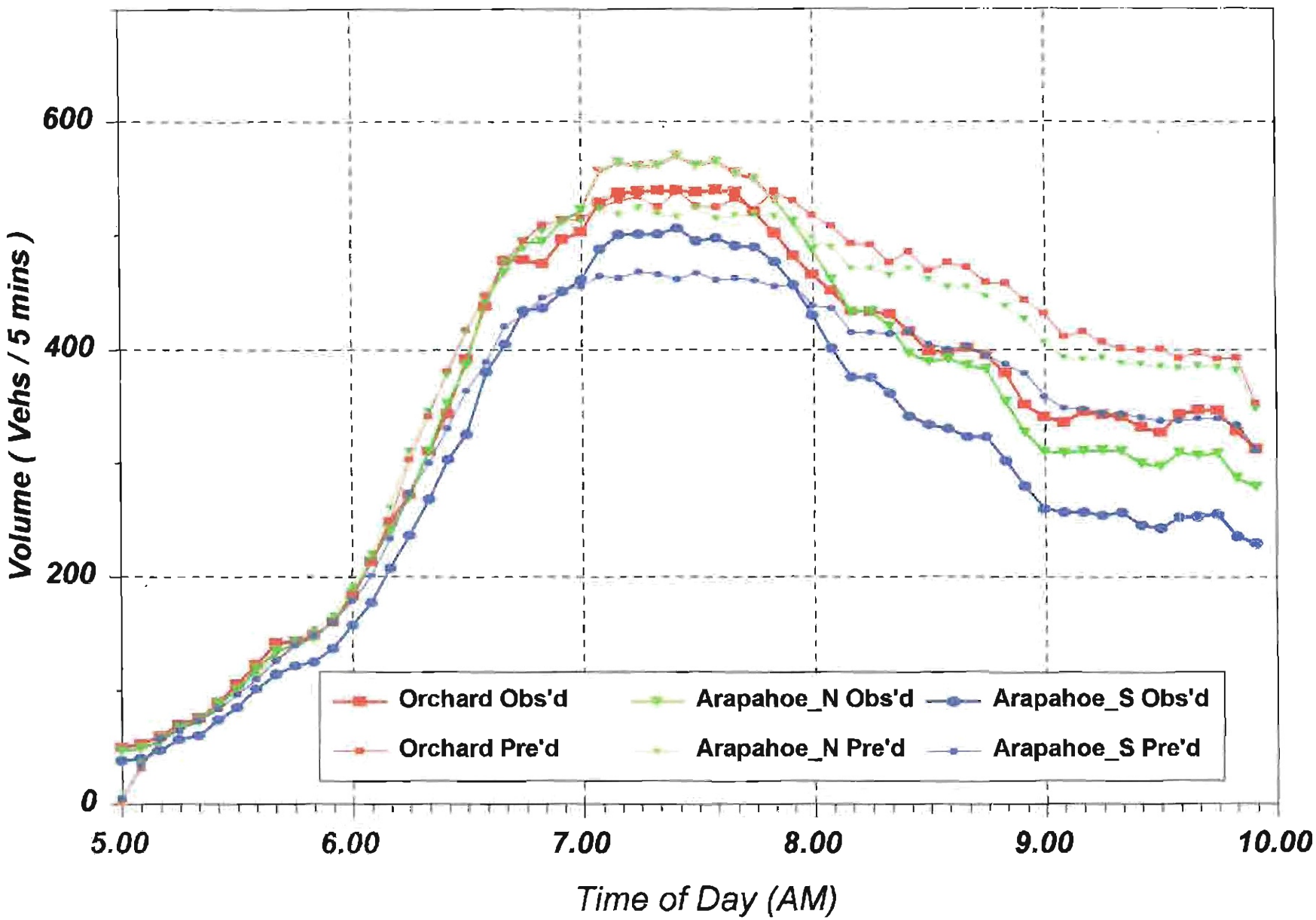

Figure 2b: Predicted vs. Observed I-25 Volumes

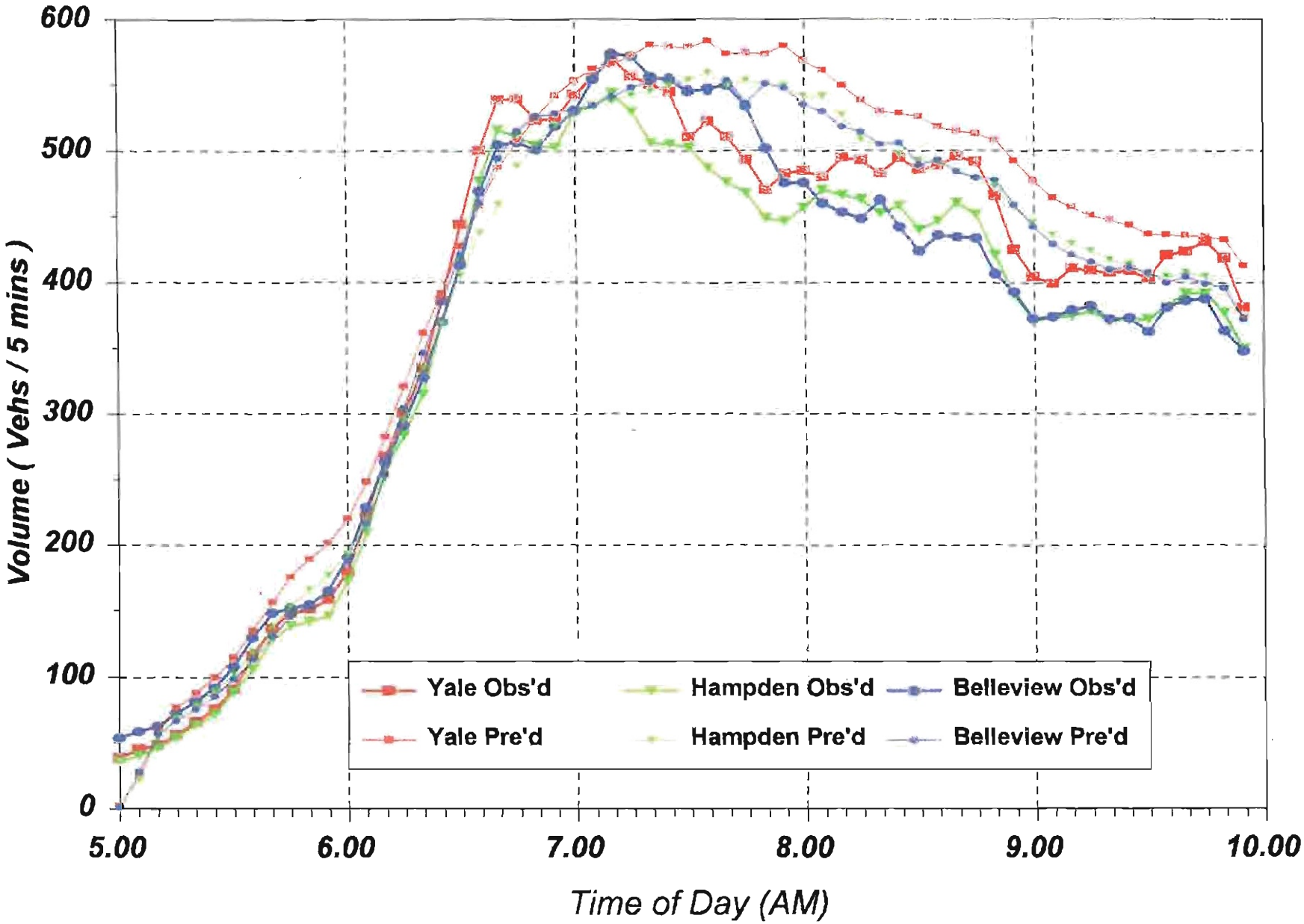

Figure 2c: Predicted vs. Observed I-25 Volumes

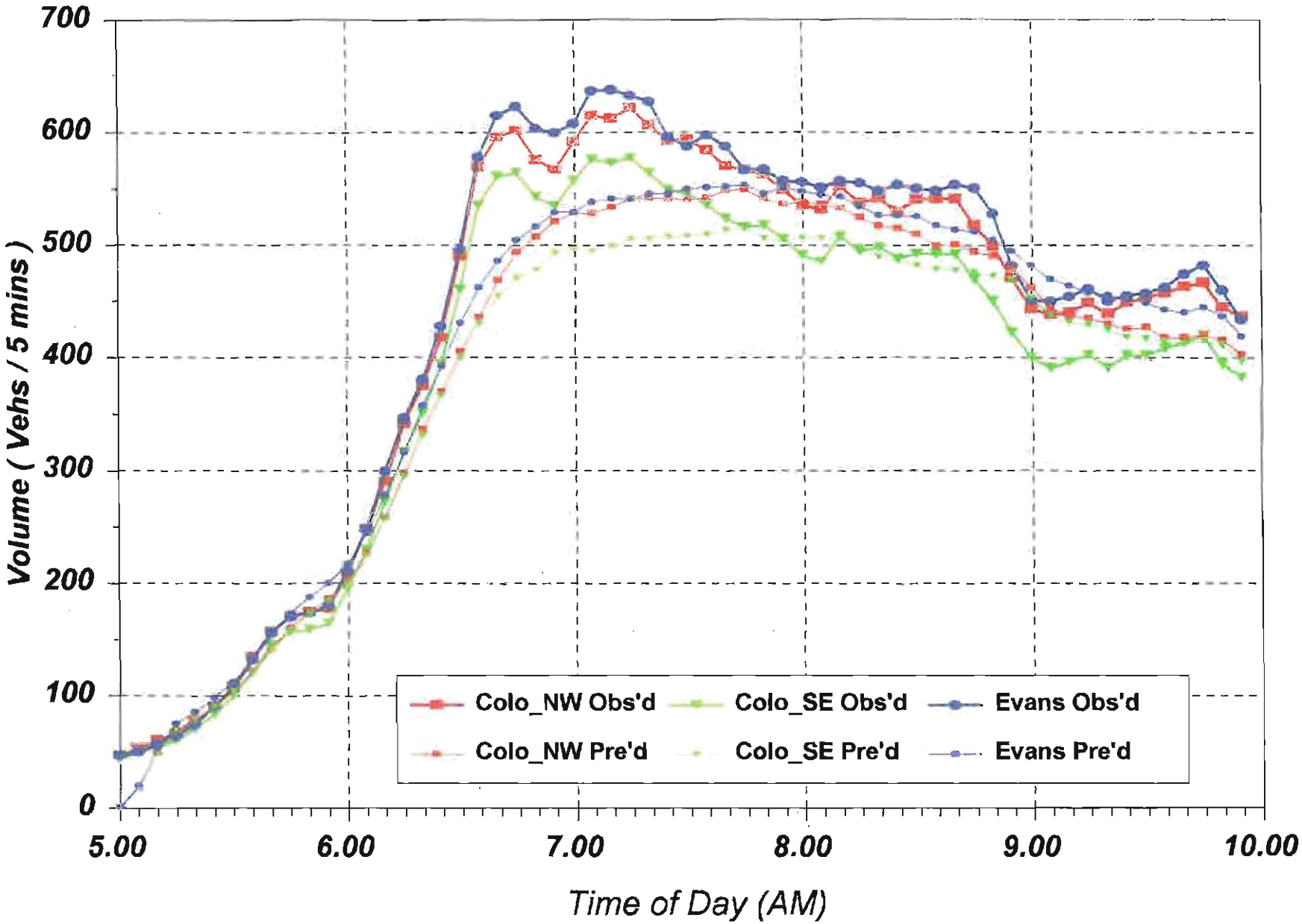

Figure 2d: Predicted vs. Observed I-25 Volumes

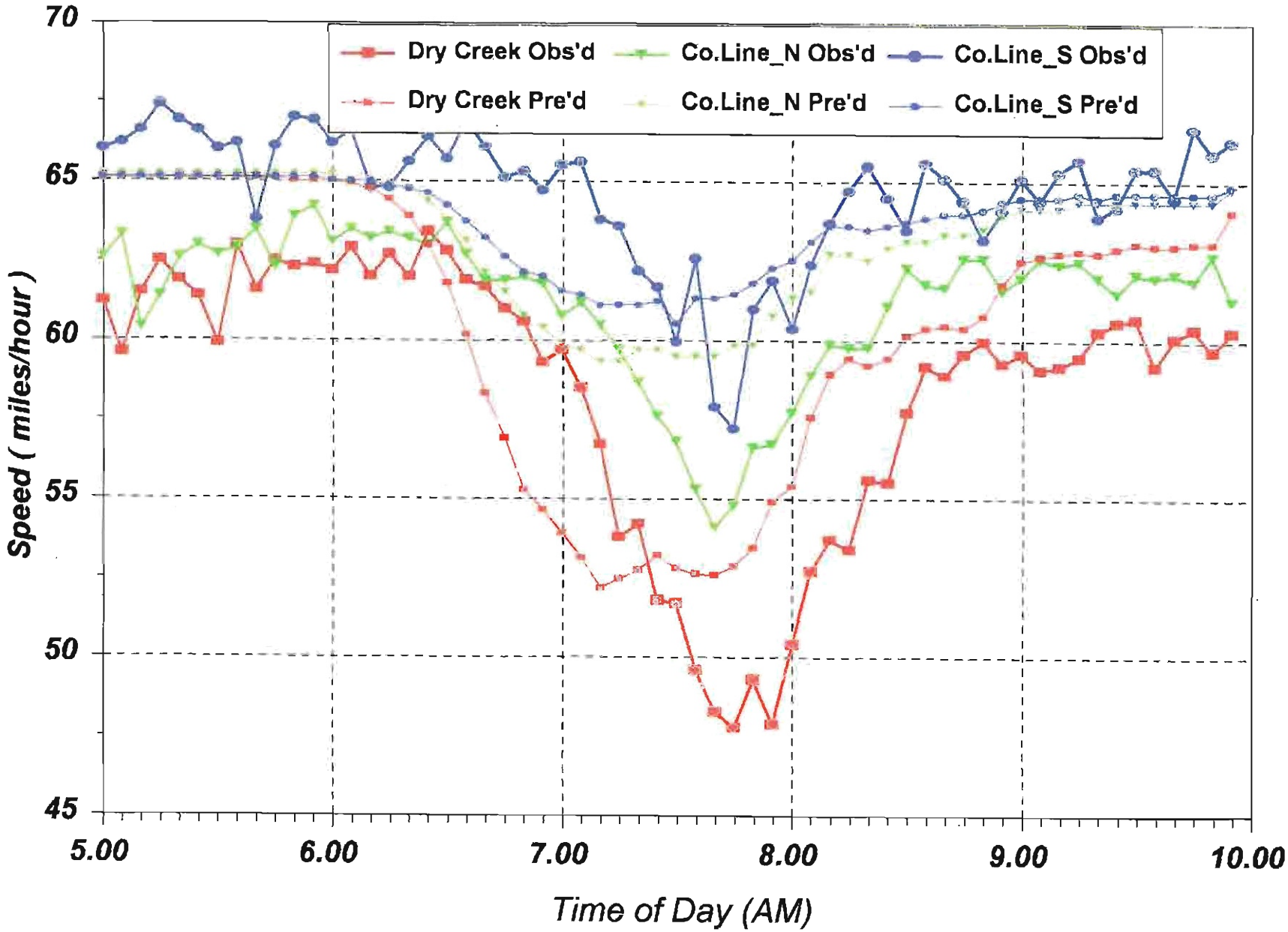

Figure 3a: Predicted vs. Observed I-25 Speeds

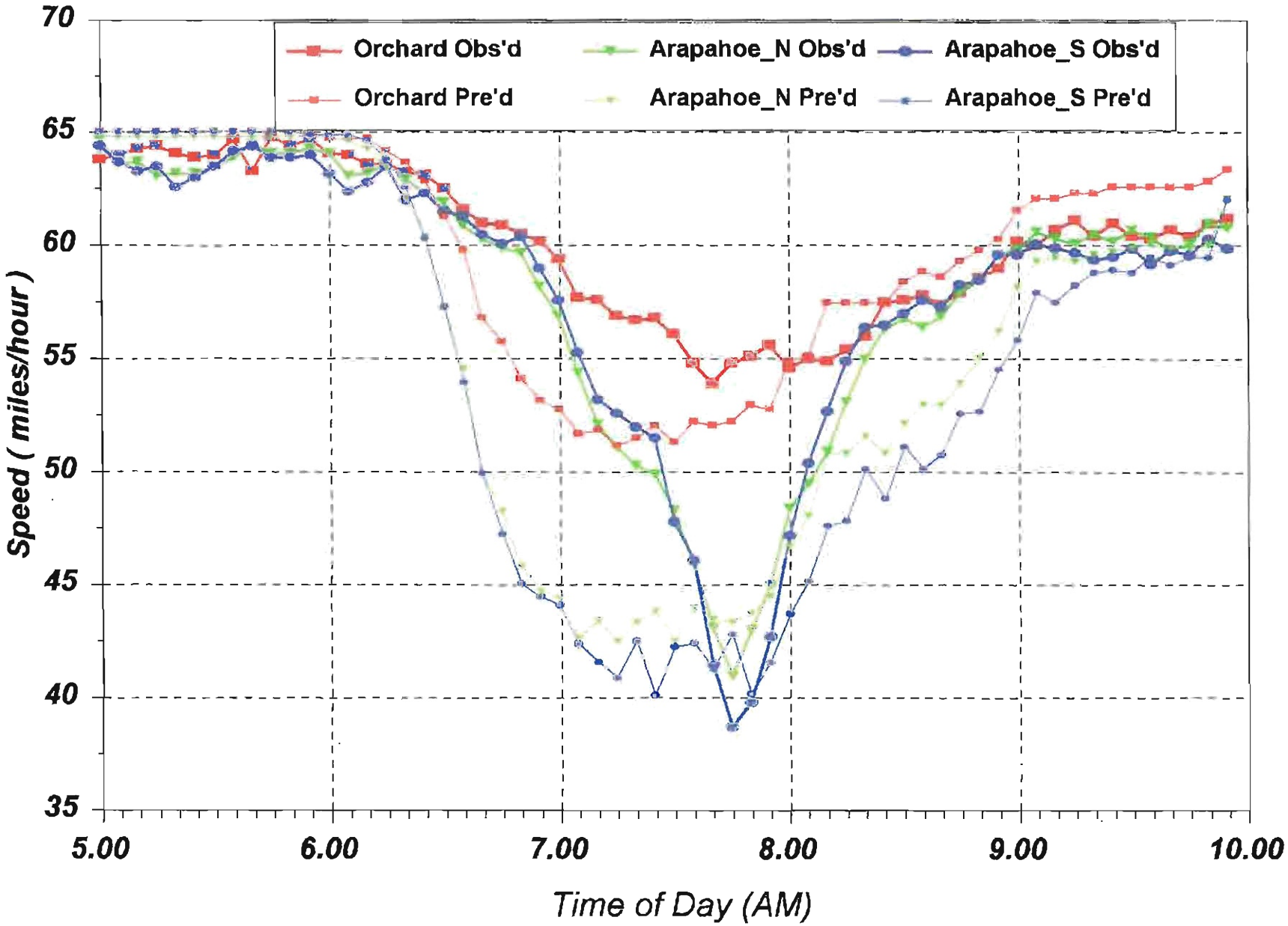

Figure 3b: Predicted vs. Observed I-25 Speeds

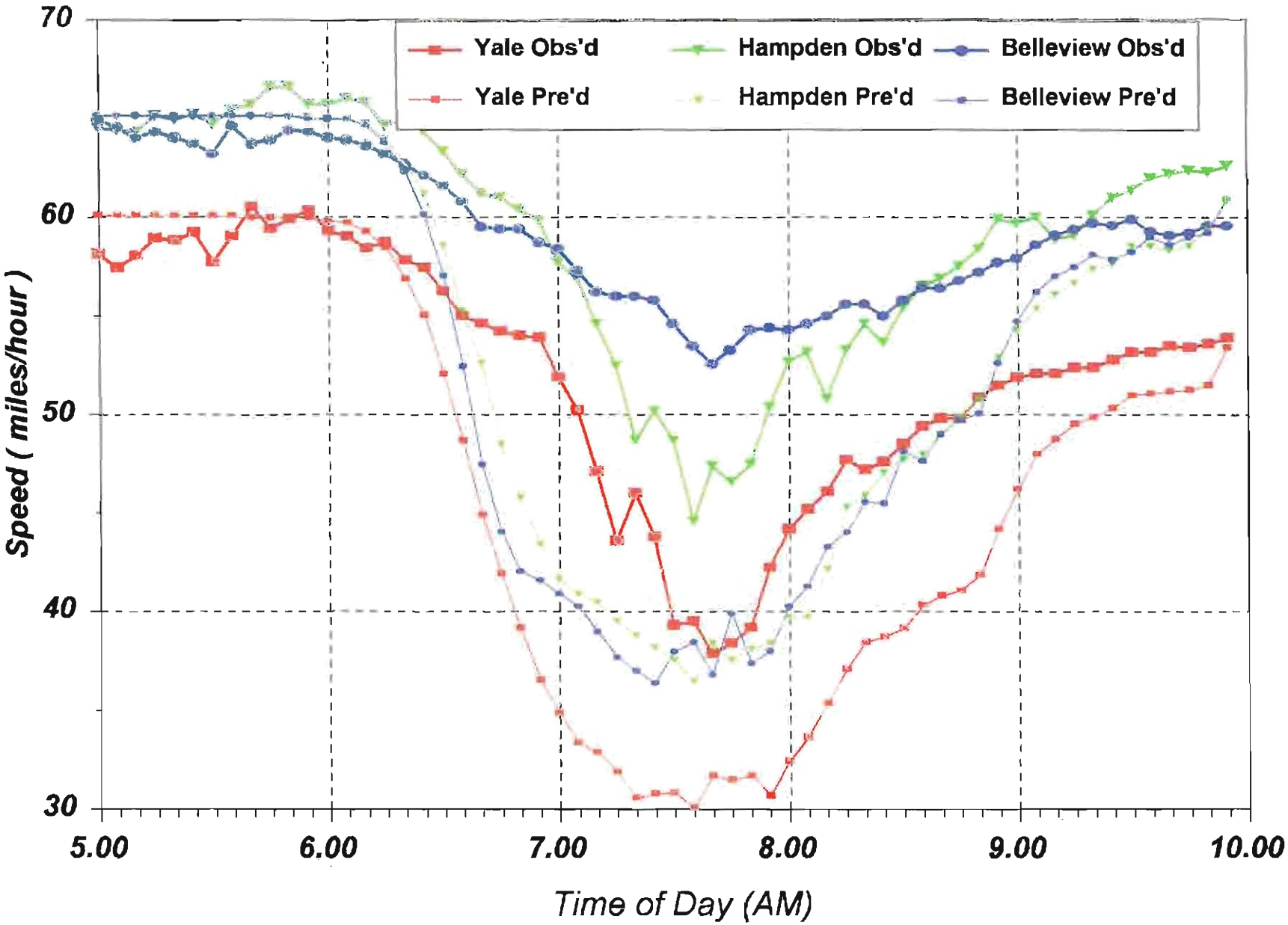

Figure 3c: Predicted vs. Observed I-25 Speeds

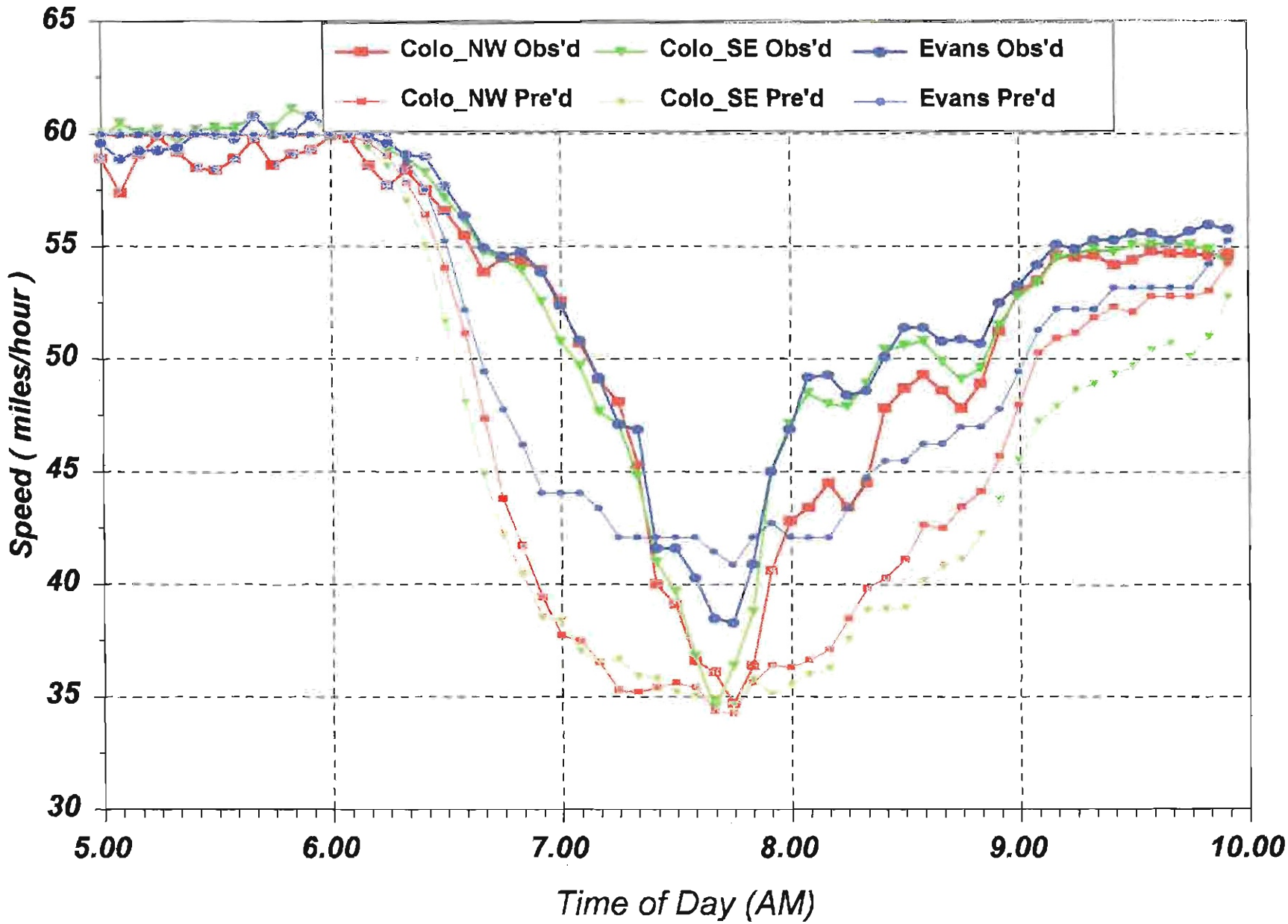

Figure 3d: Predicted vs. Observed I-25 Speeds

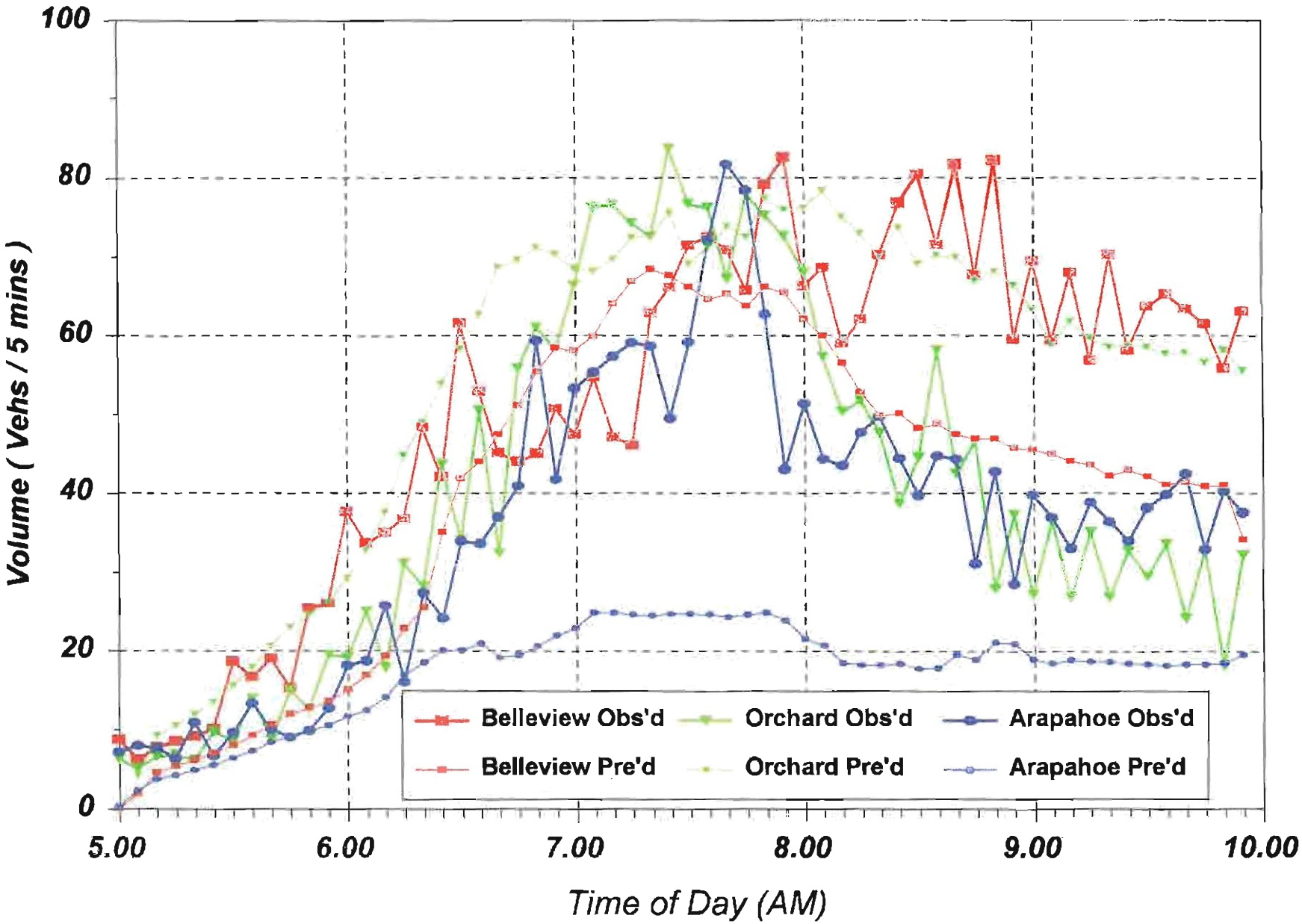

Figure 4a: Predicted vs. Observed Off-Ramp Volumes

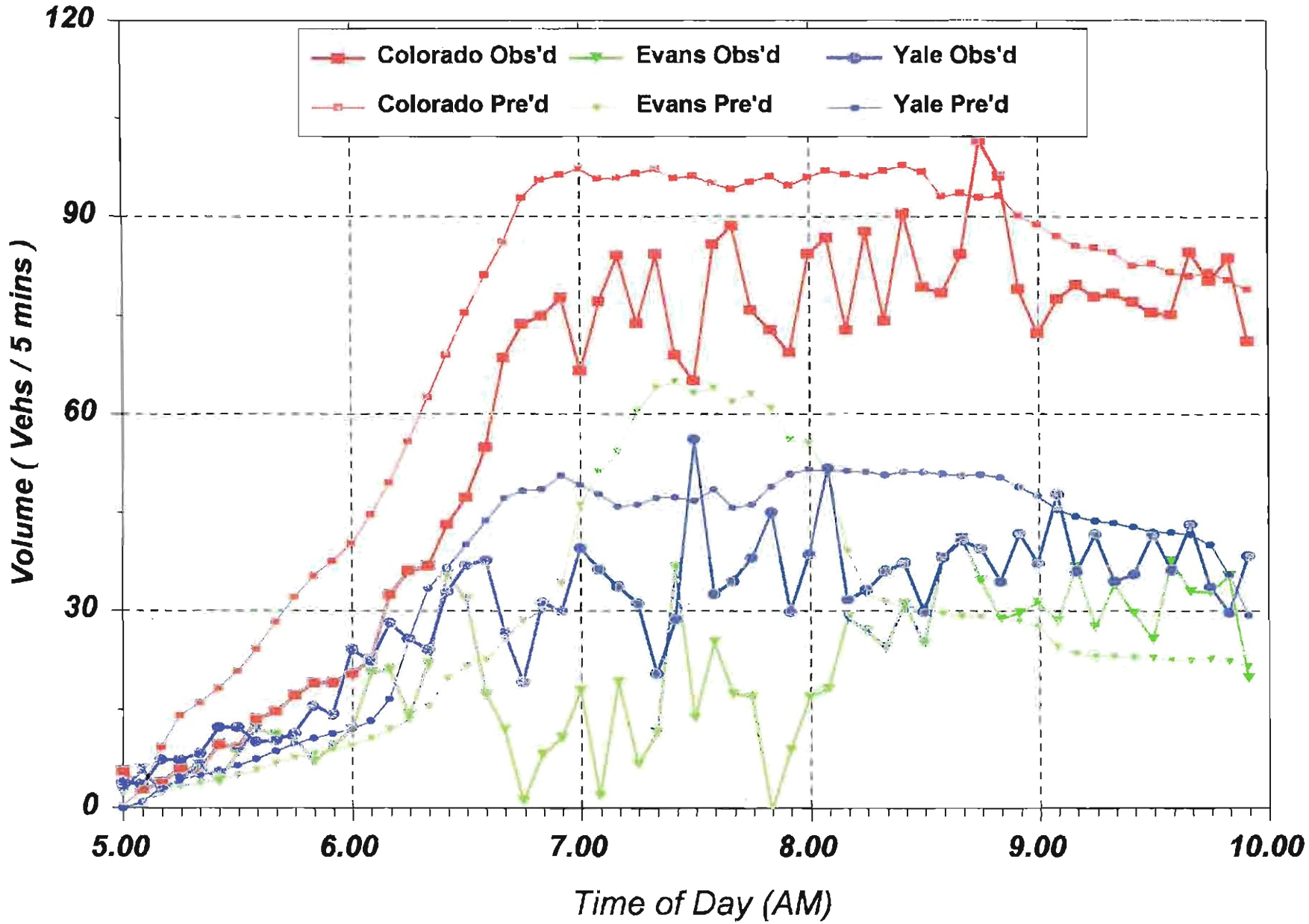

Figure 4b: Predicted vs. Observed Off-Ramp Volumes

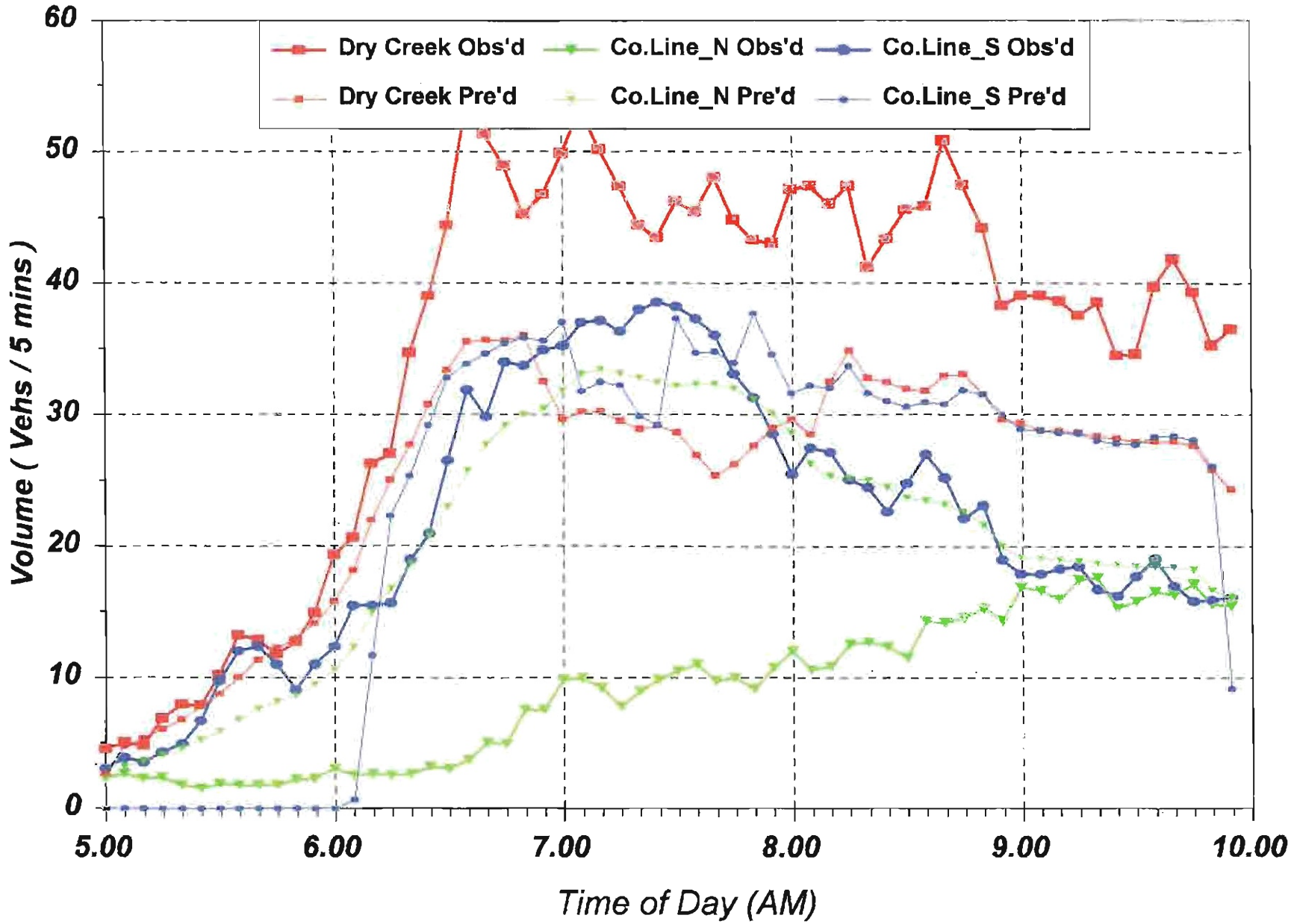

Figure 5a: Predicted vs. Observed On-Ramp Volumes

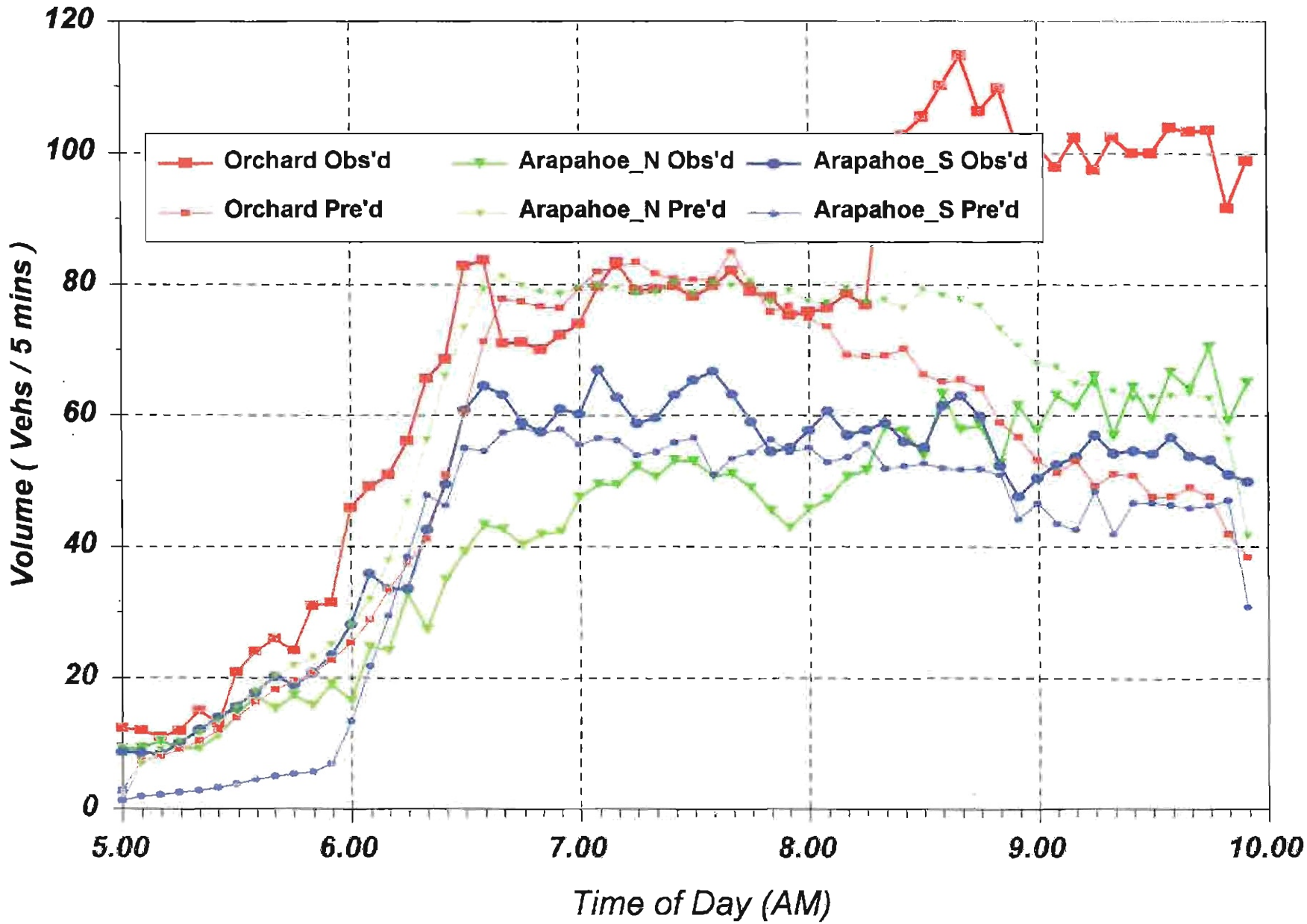

Figure 5b: Predicted vs. Observed On-Ramp Volumes

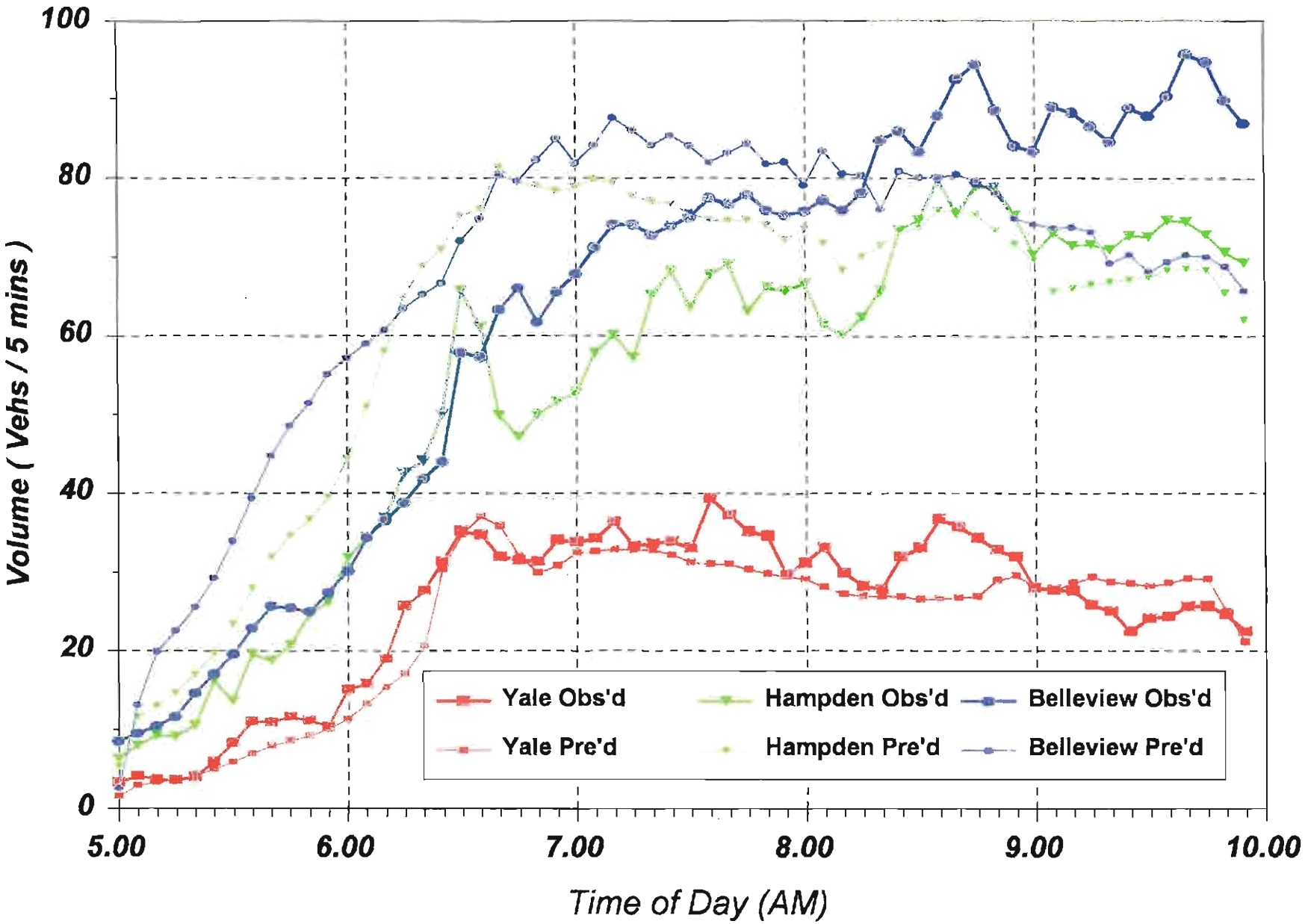

Figure 5c: Predicted vs. Observed On-Ramp Volumes

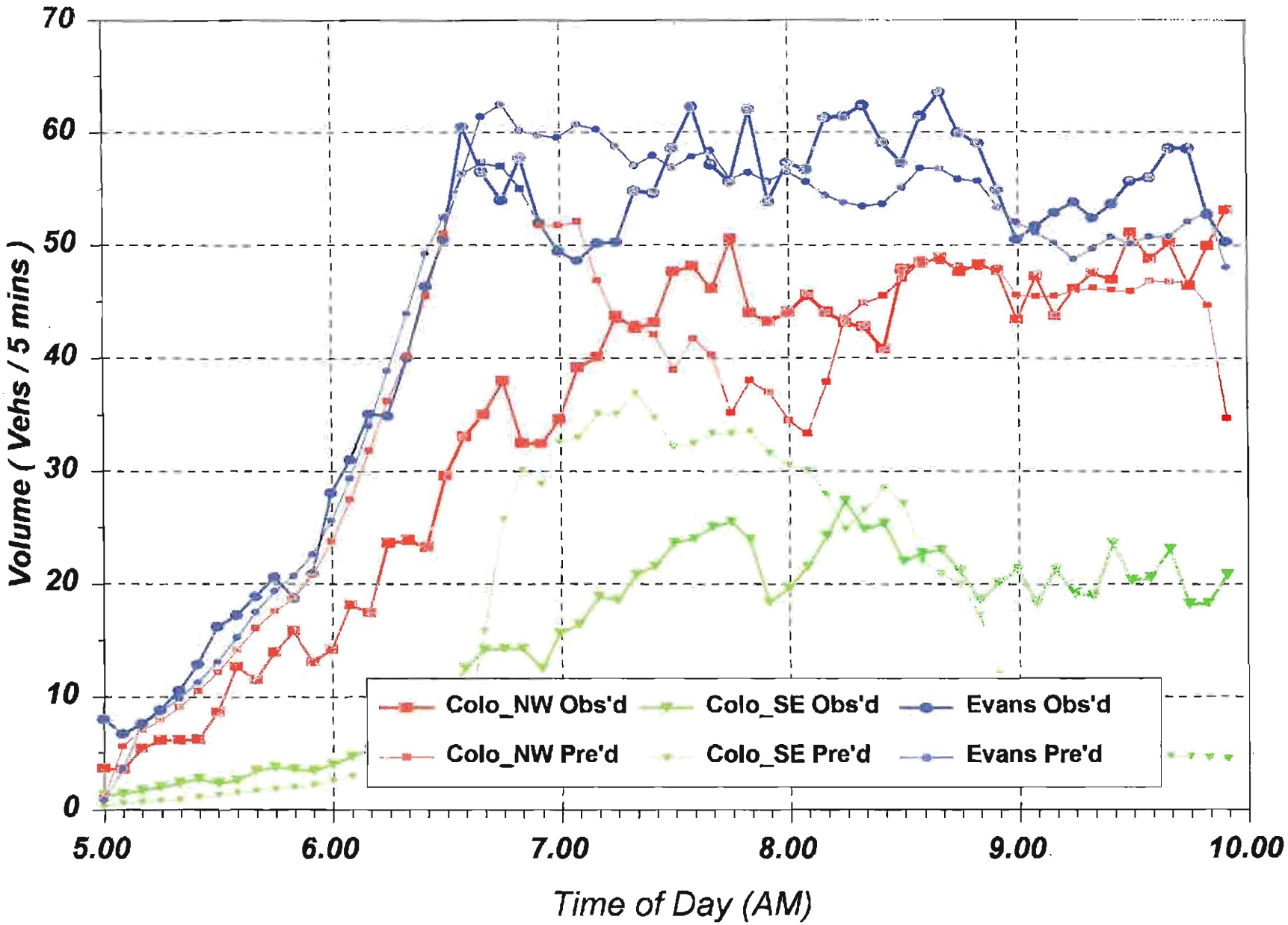

Figure 5d: Predicted vs. Observed On-Ramp Volumes

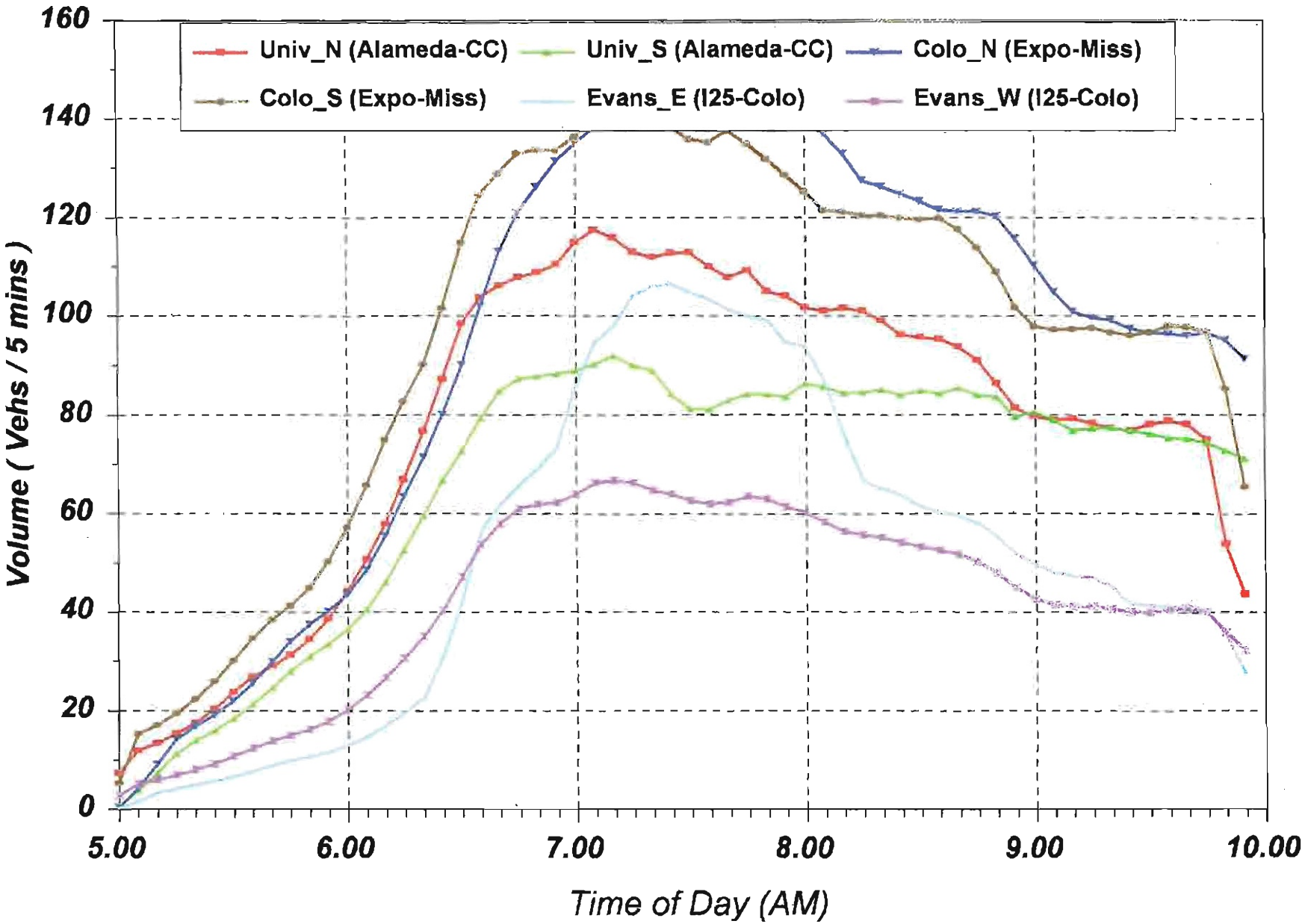

Figure 6a: Predicted Arterial Link Volumes

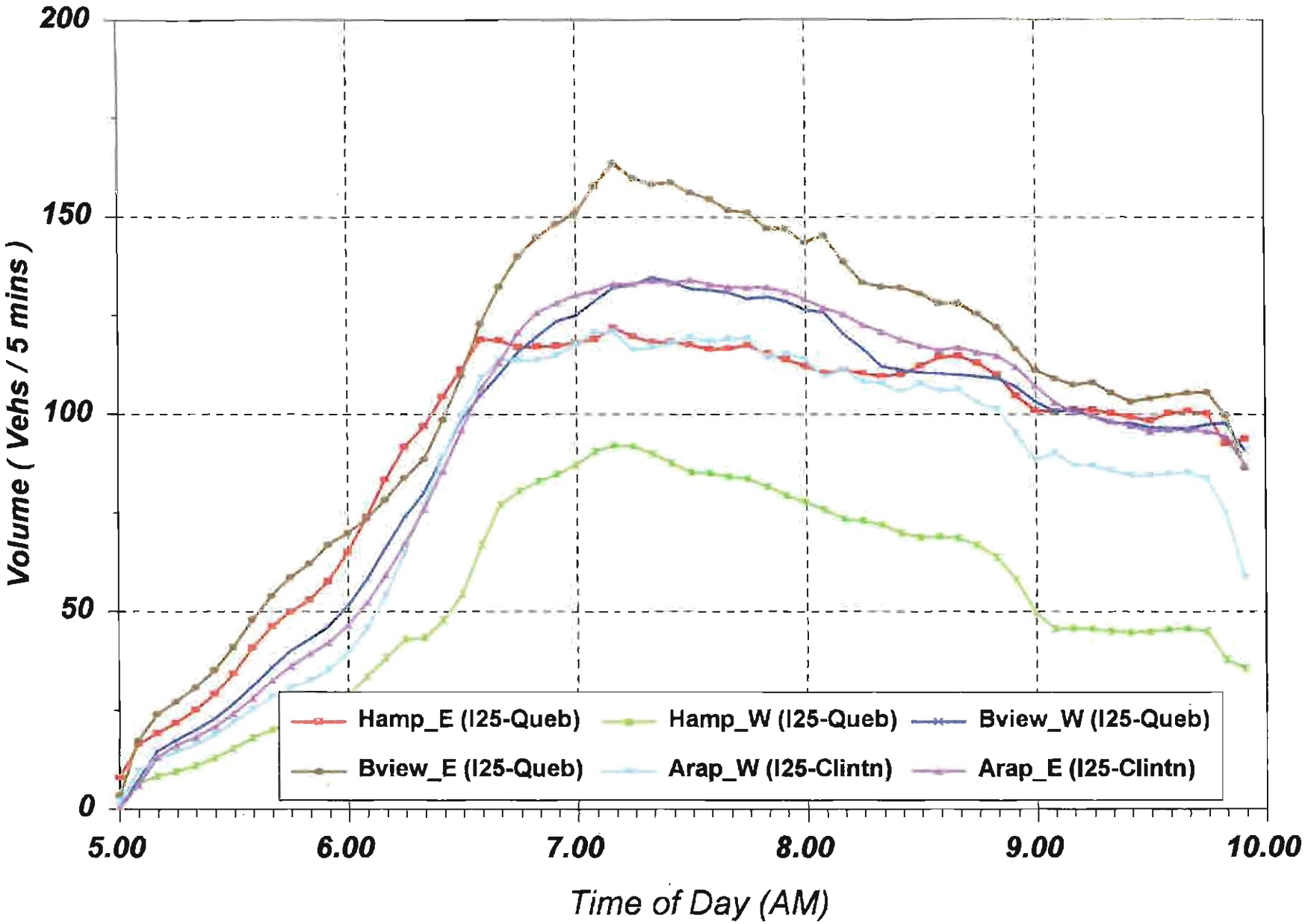

Figure 6b: Predicted Arterial Link Volumes

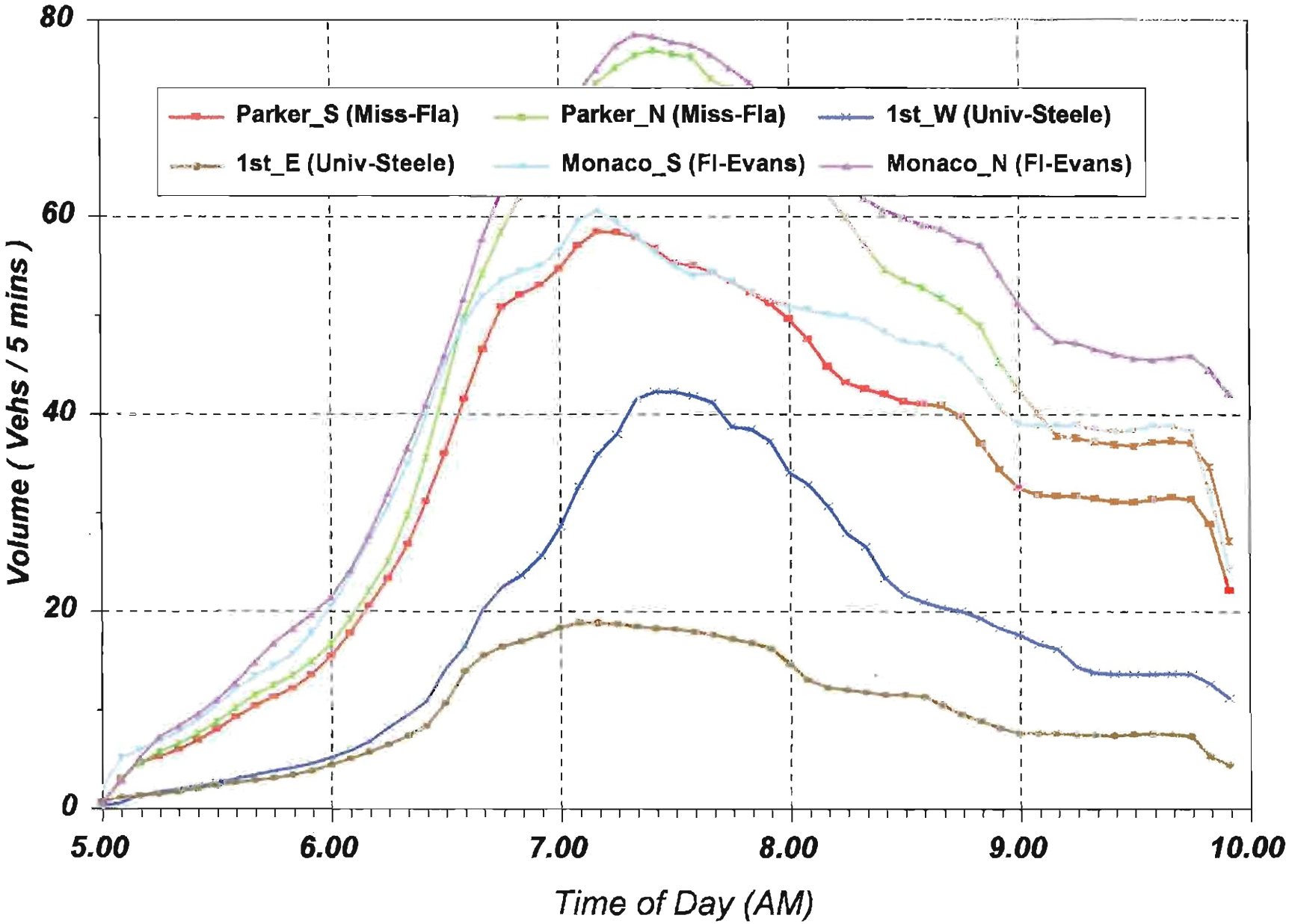

Figure 6c: Predicted Arterial Link Volumes

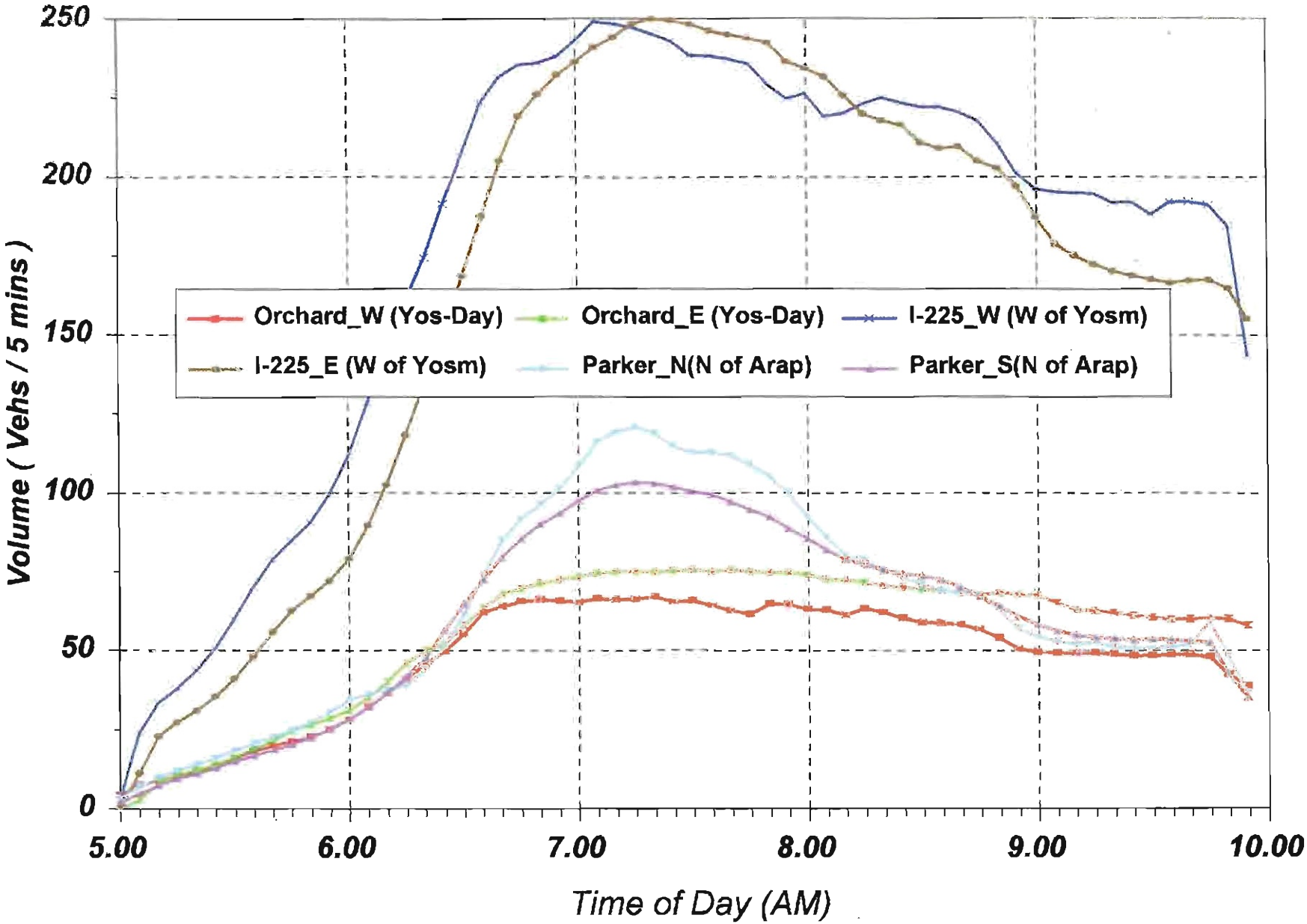

Figure 6d: Predicted Arterial Link Volumes

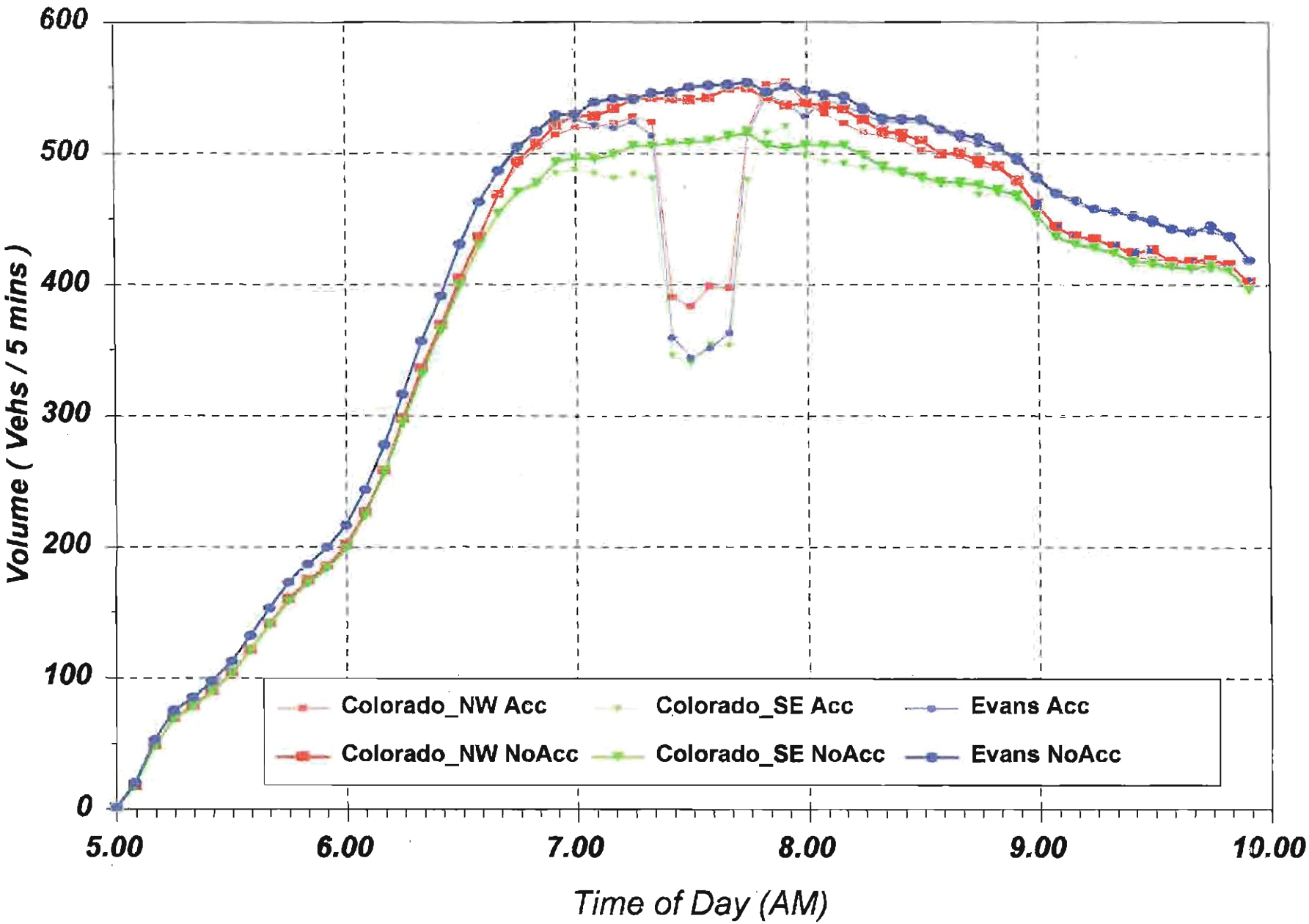

Figure 7a: Predicted I-25 Volumes (Acc. # 1 vs. No Acc.)

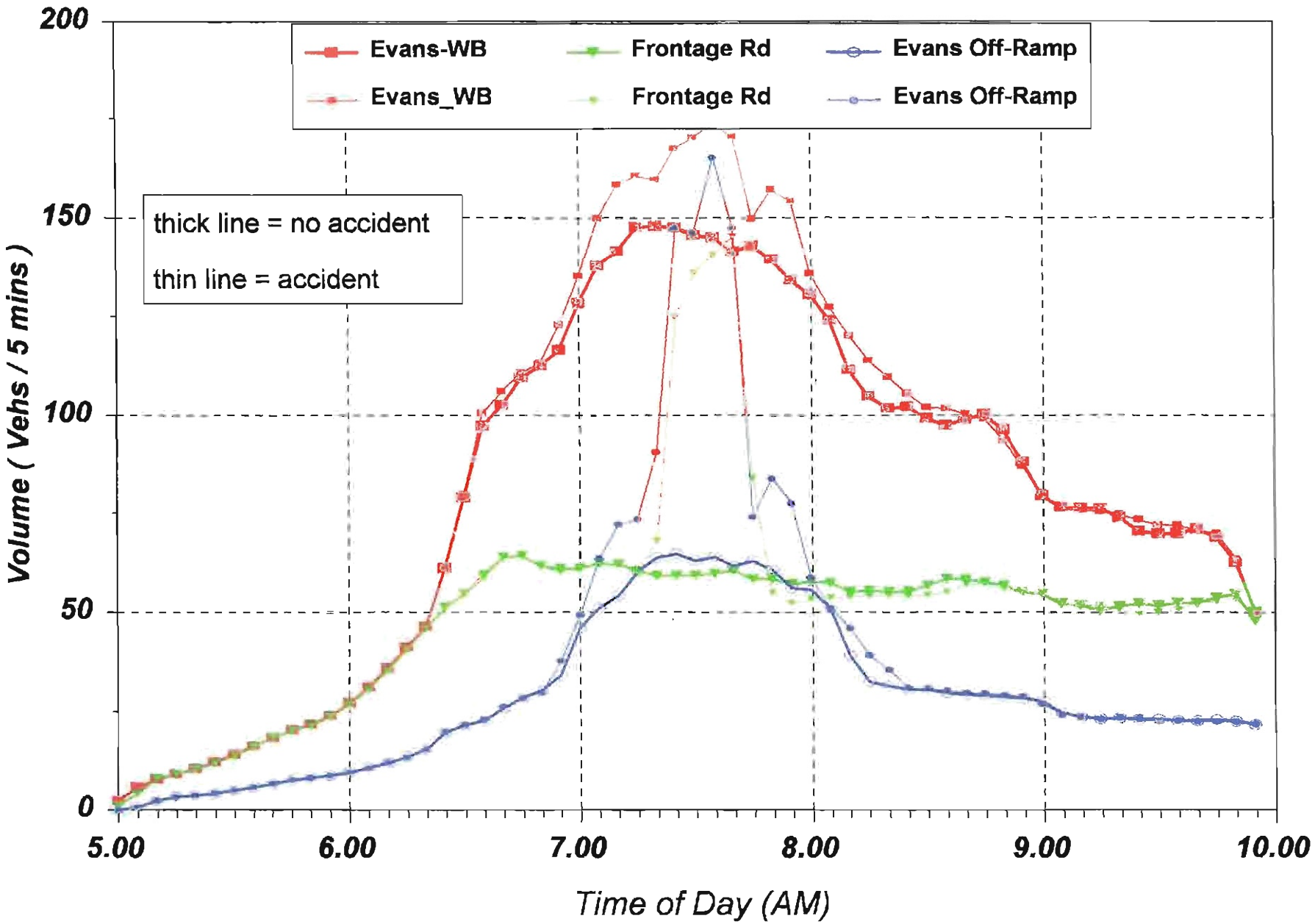

Figure 7b: Predicted Alt. Rt. Volumes (Acc. # 1 vs. No Acc.)

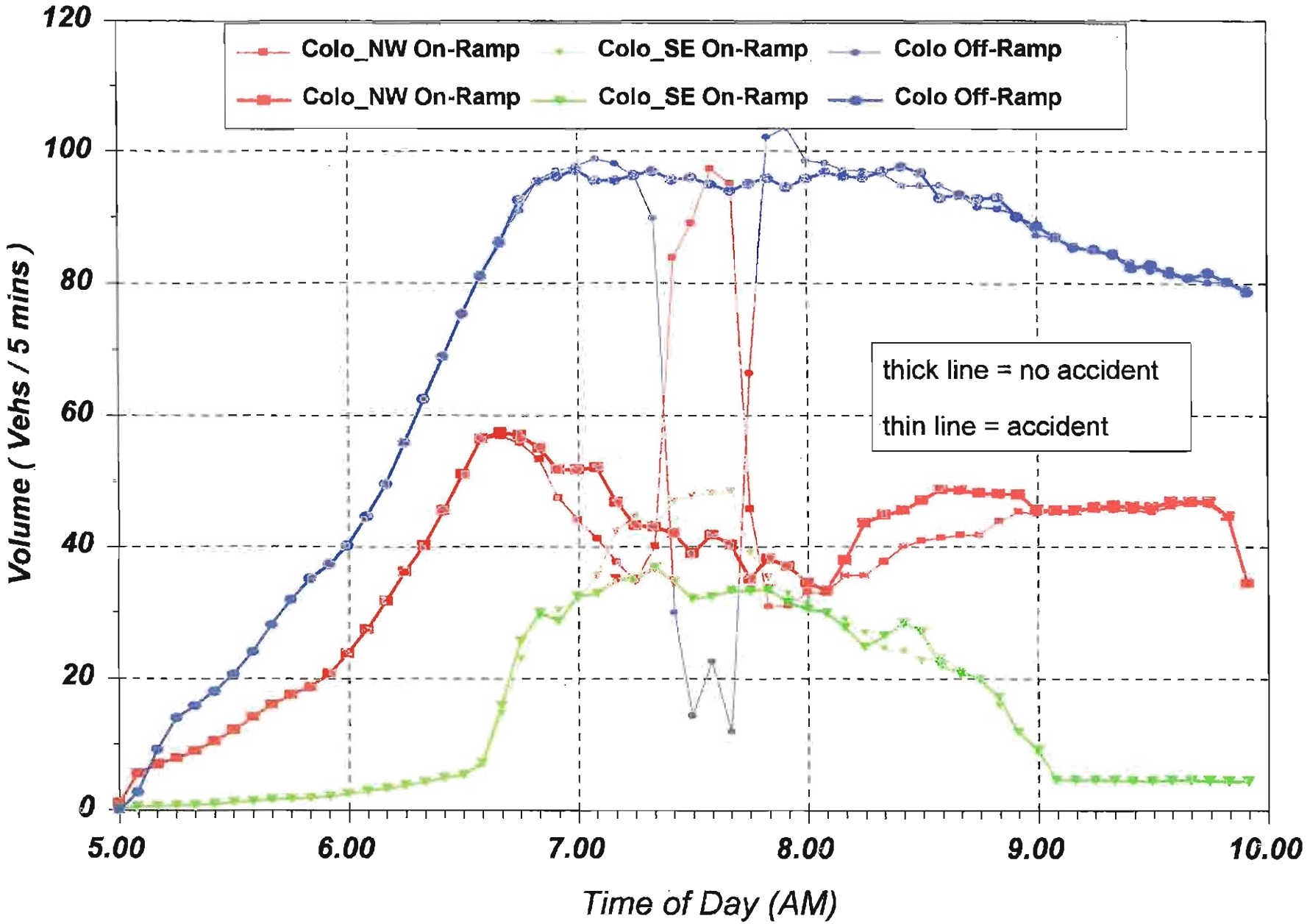

Figure 7c: Predicted Ramp Volumes (Acc. # 1 vs. No Acc.)

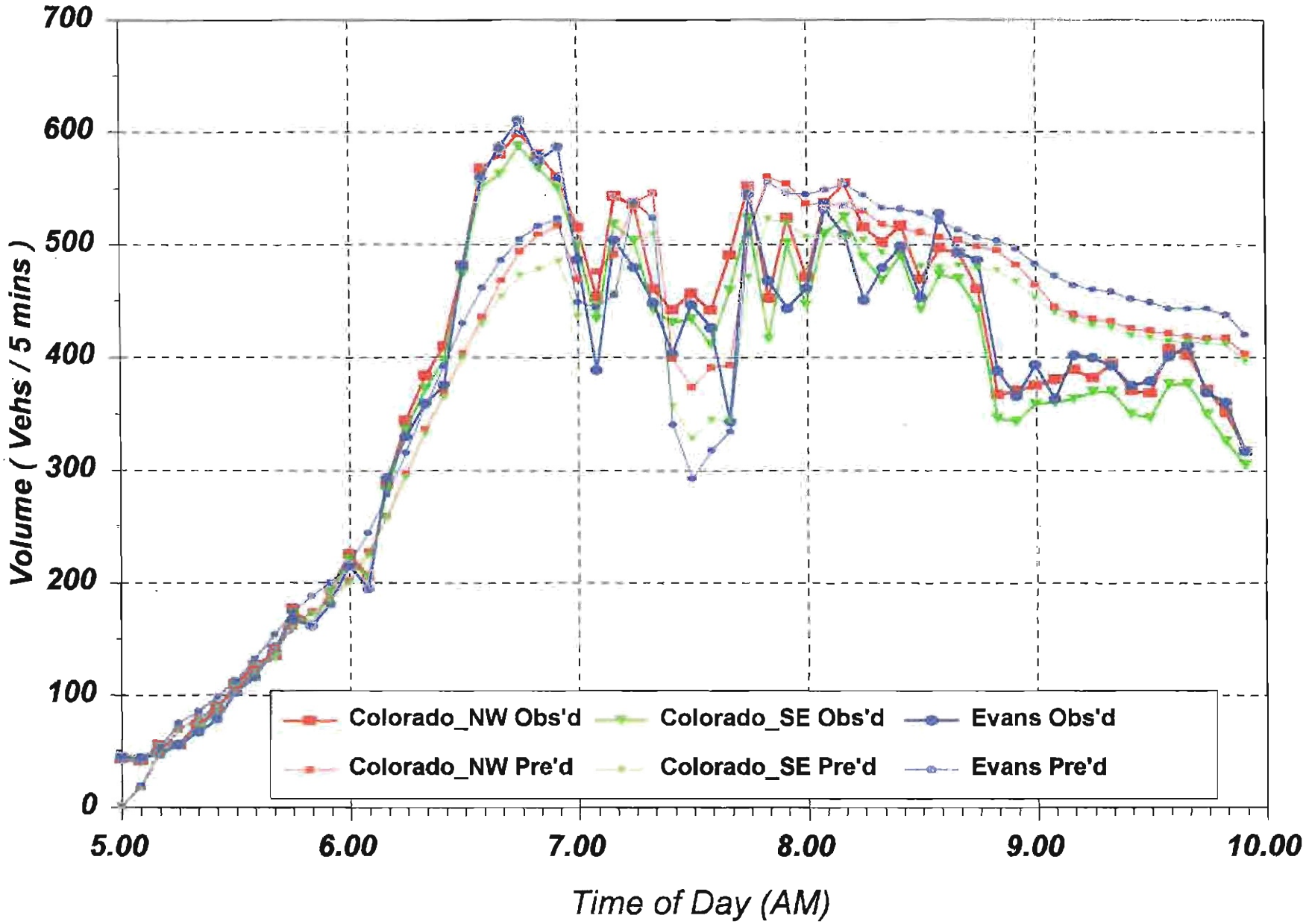

Figure 7d: Pred. vs. Obs. I-25 Volumes (Accident # 1)

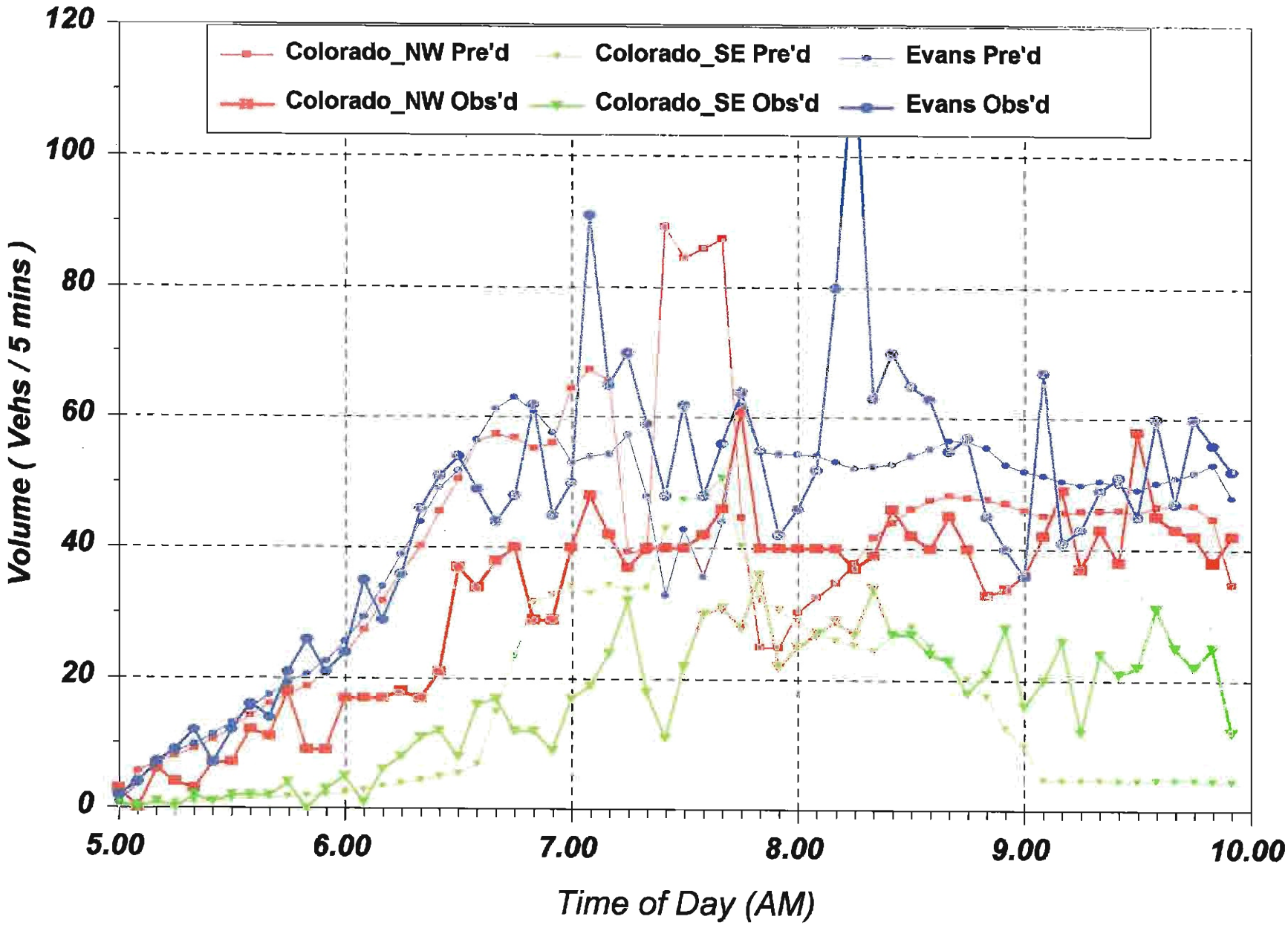

Figure 7e: Pred. vs. Obs. On-Ramp Volumes (Accident # 1)

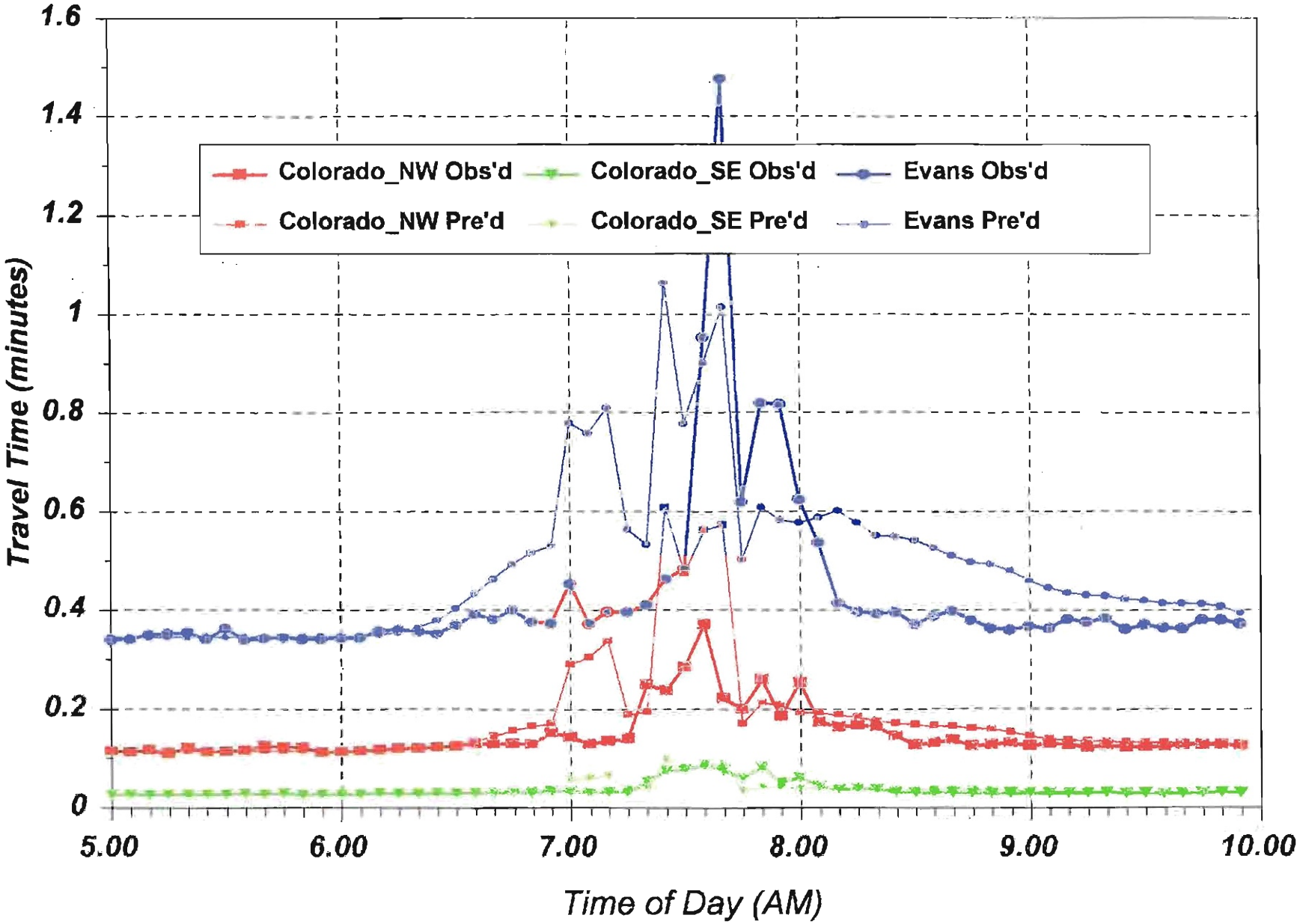

Figure 7f: Pred. vs. Obs. I-25 Times (Accident # 1)

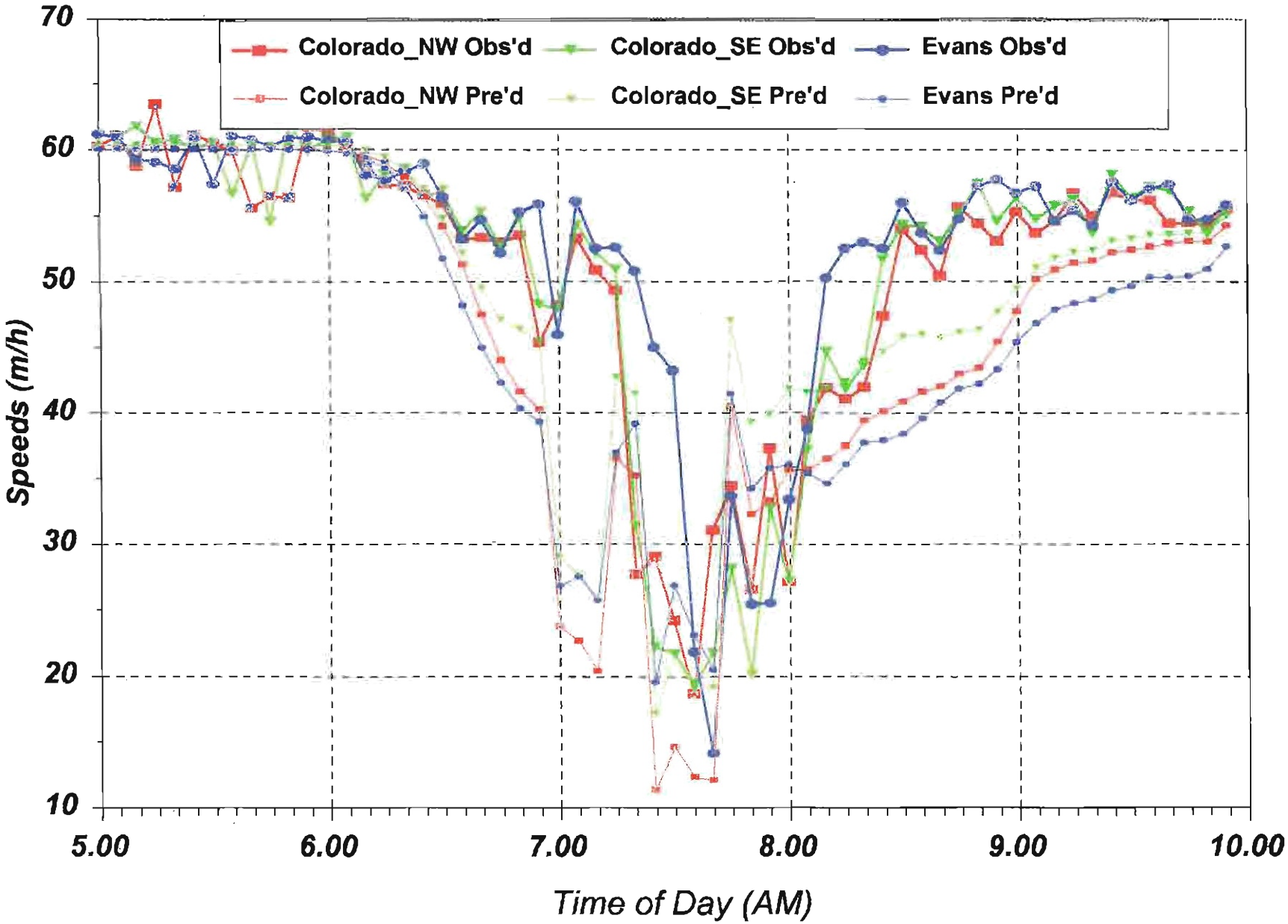

Figure 7g: Pred. vs. Obs. I-25 Speeds (Accident # 1)

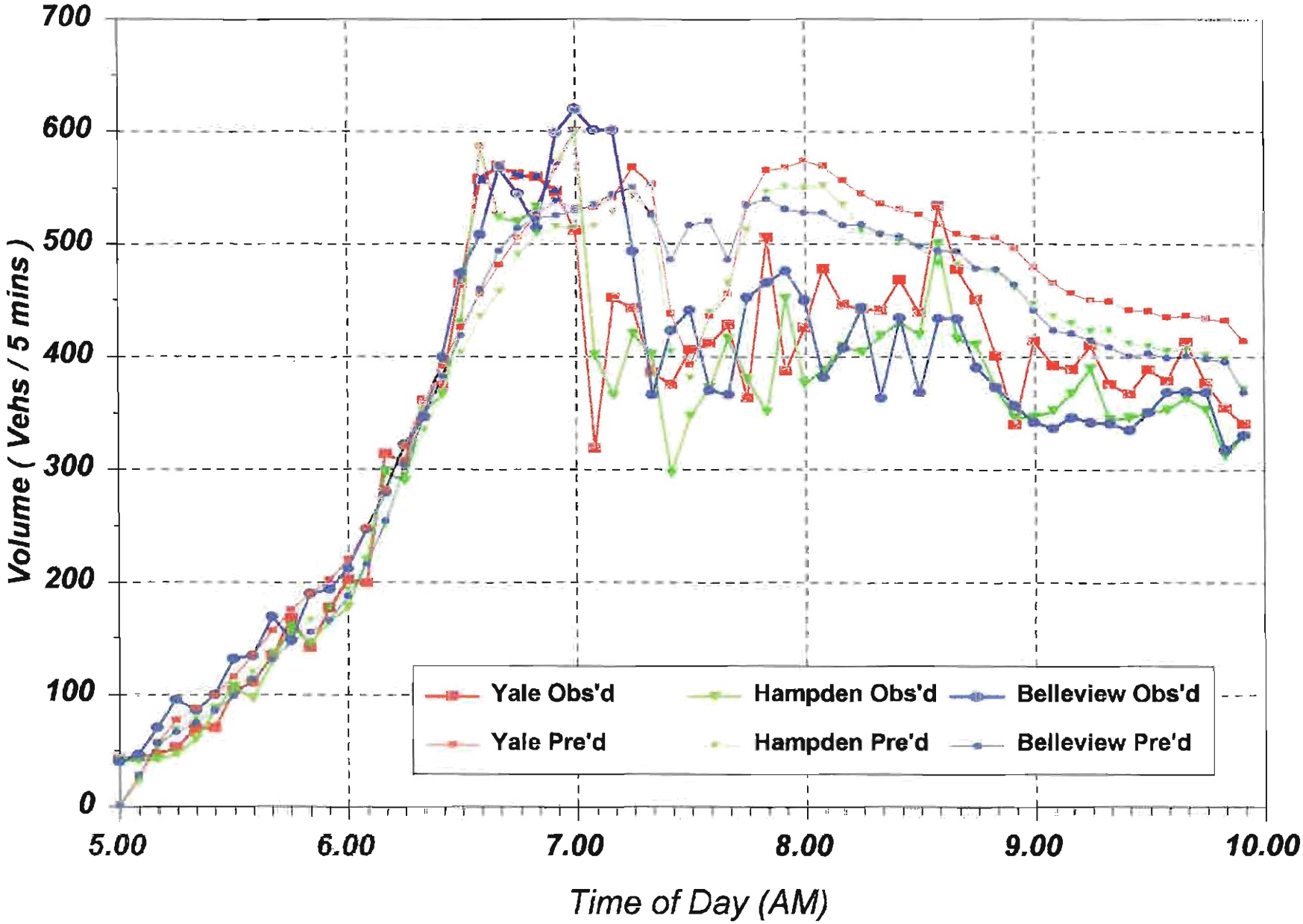

Figure 7h: Pred. vs. Obs. I-25 Upstream Volumes (Accident # 1)

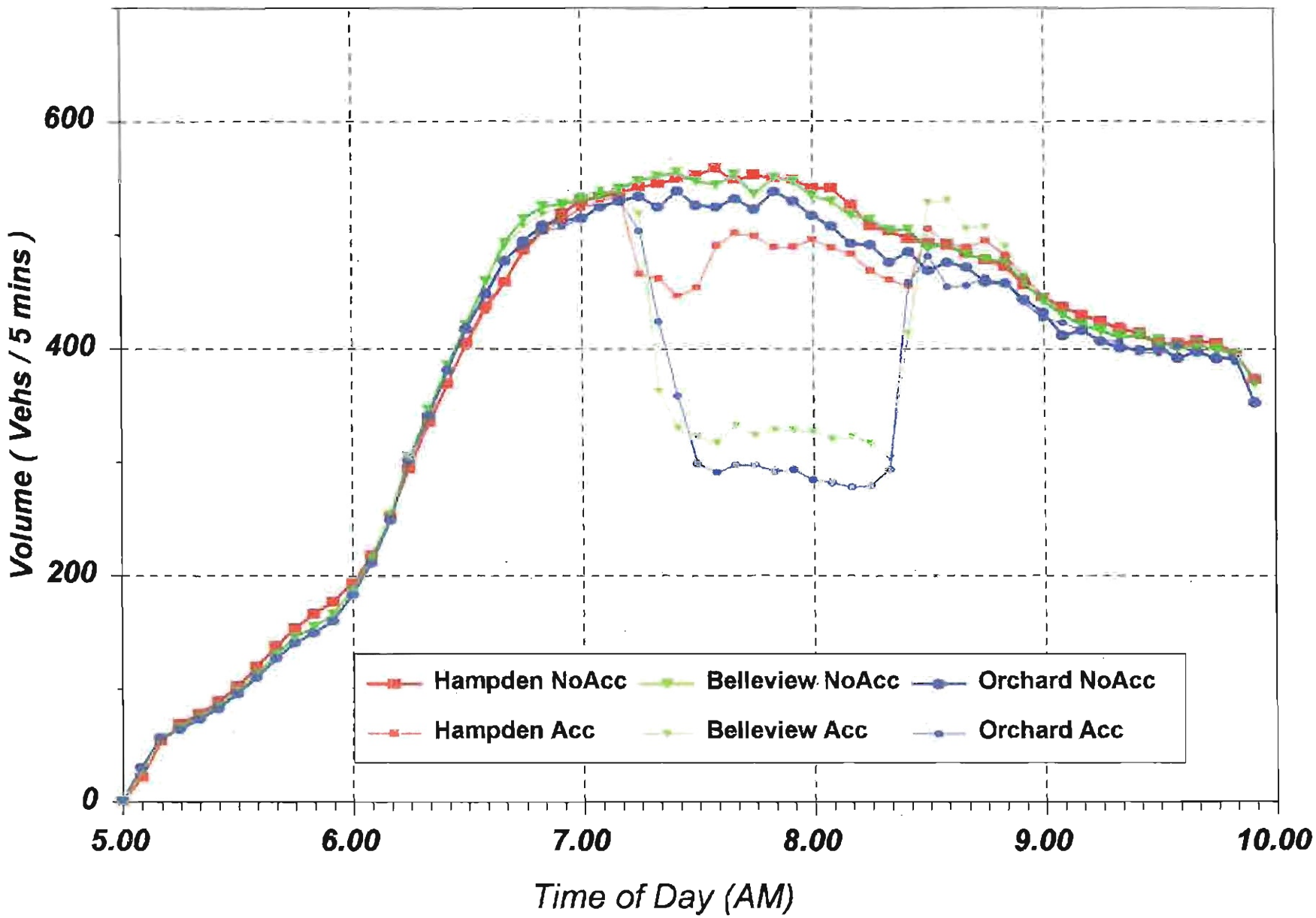

Figure 8a: Predicted I-25 Volumes (Acc. # 2 vs. No Acc.)

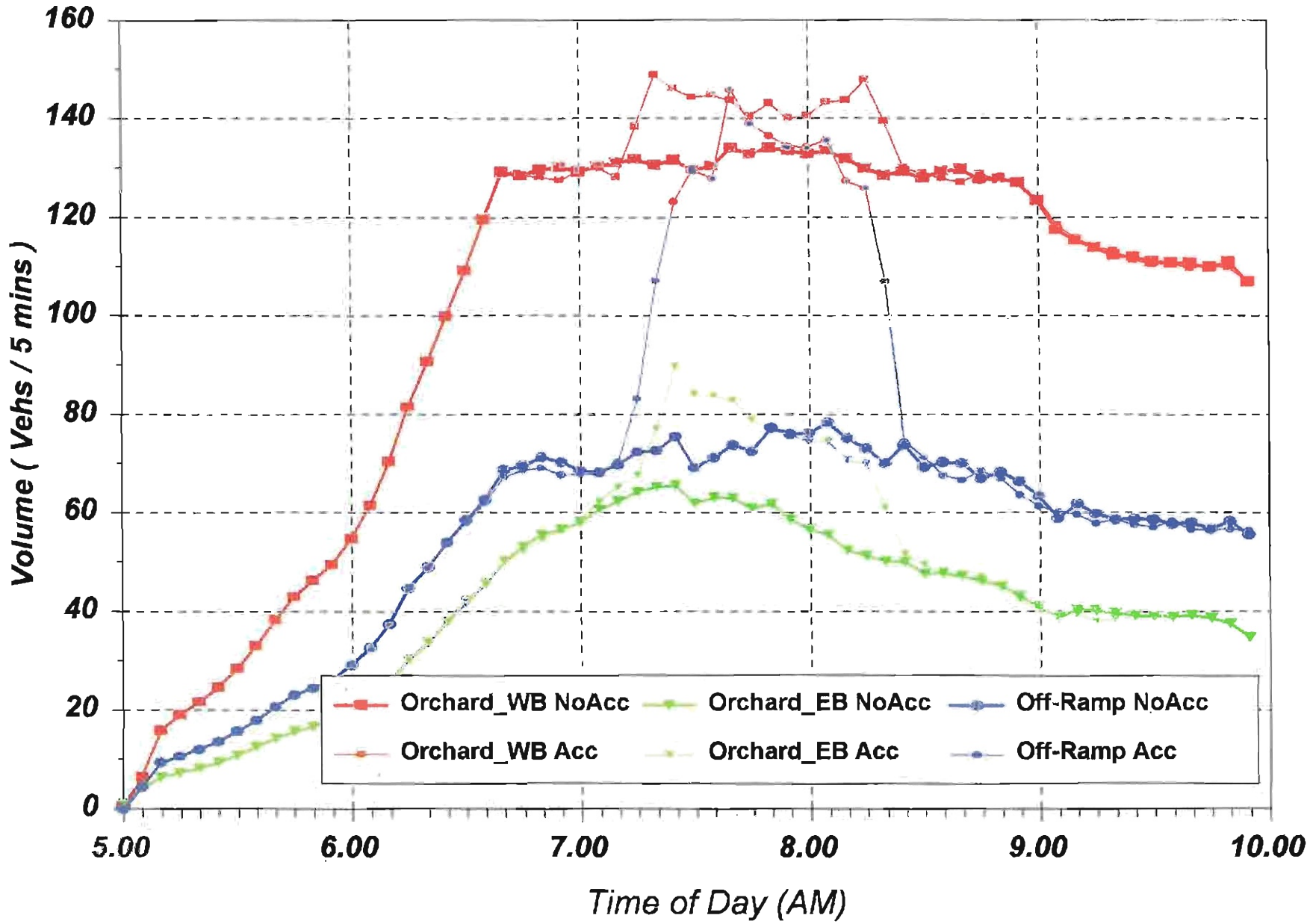

Figure 8b: Predicted Alt. Rt. Volumes (Acc. # 2 vs. No Acc.)

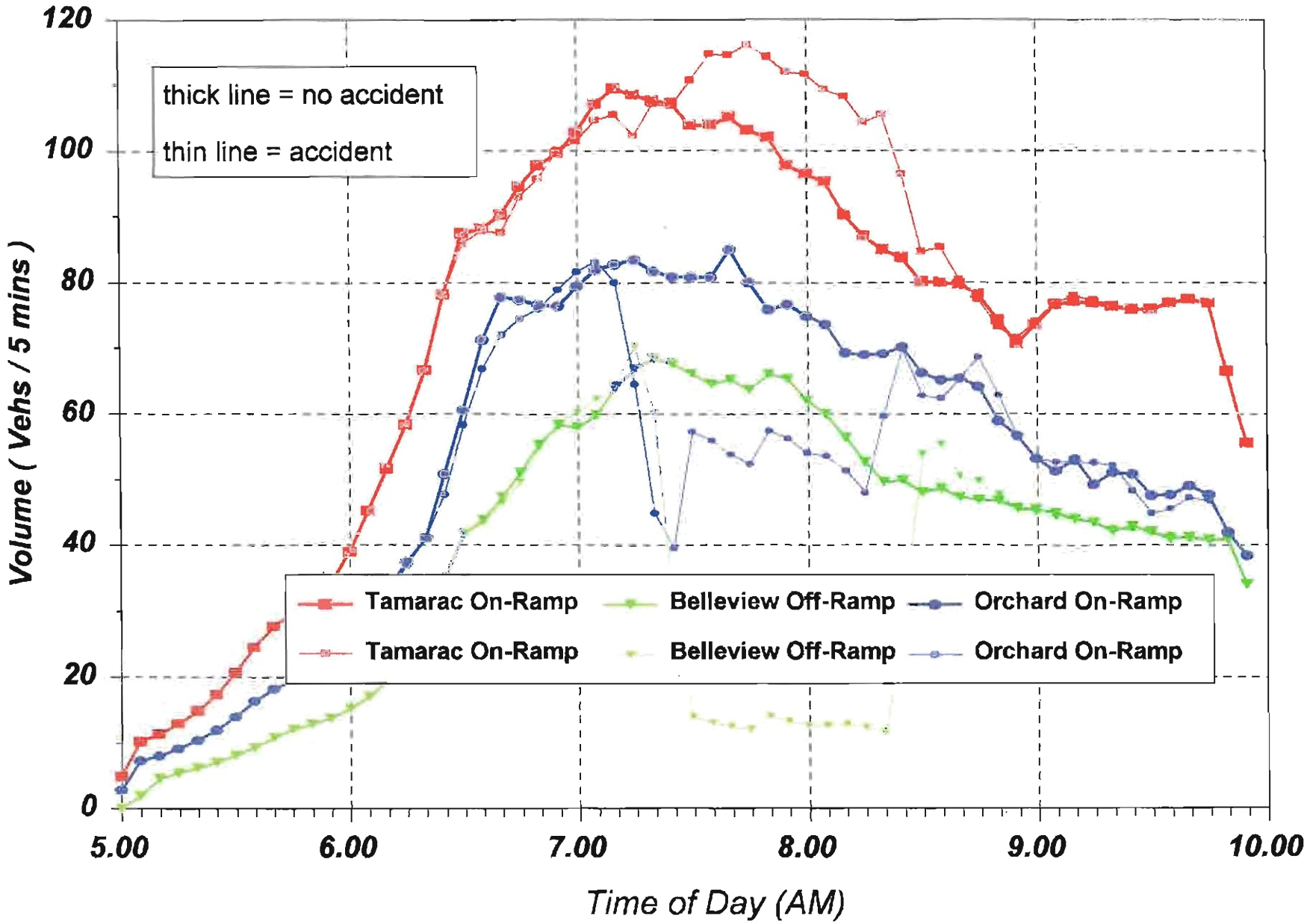

Figure 8c: Predicted Ramp Volumes (Acc. # 2 vs. No Acc.)

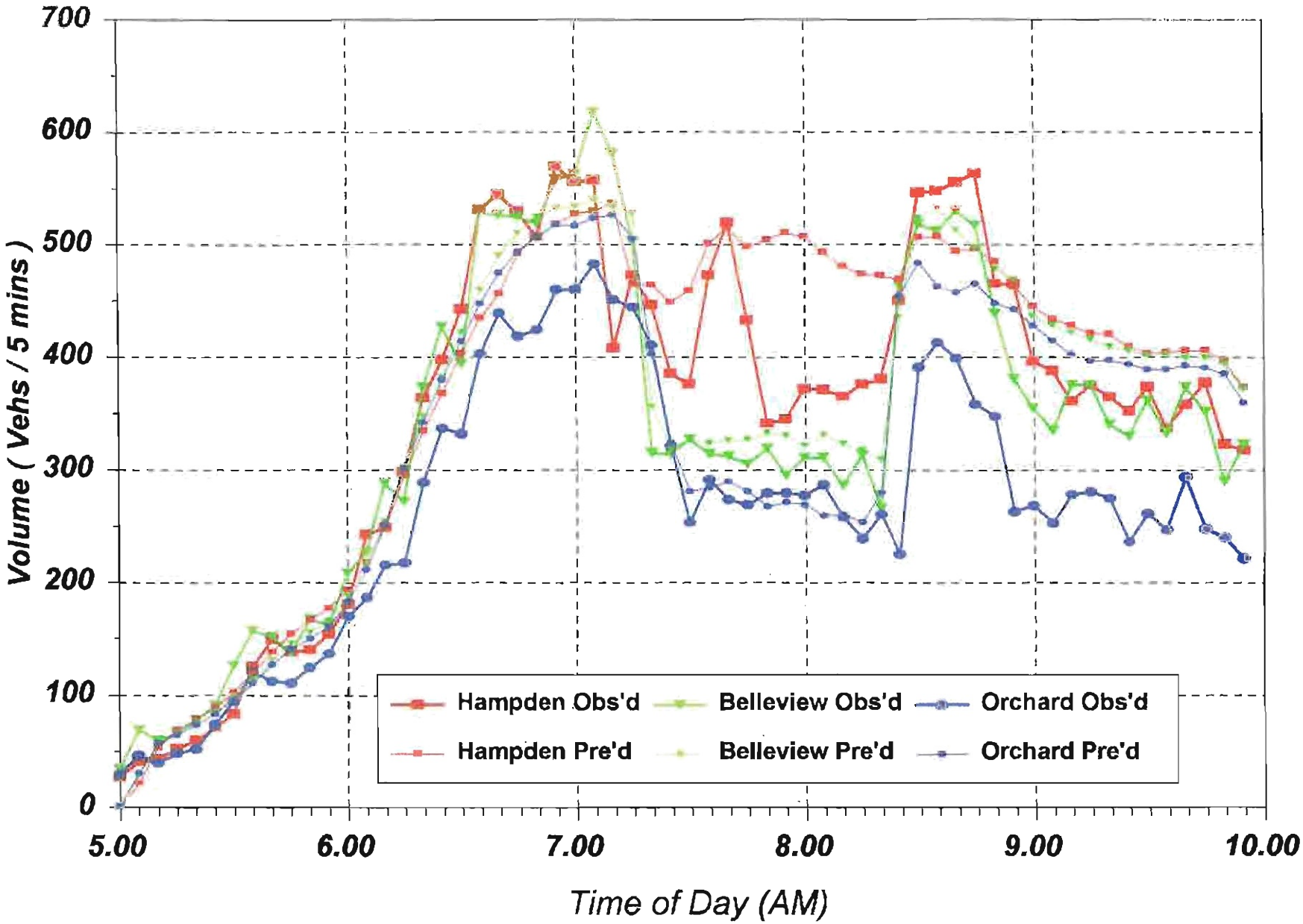

Figure 8d: Pred. vs. Obs. I-25 Volumes (Accident # 2)

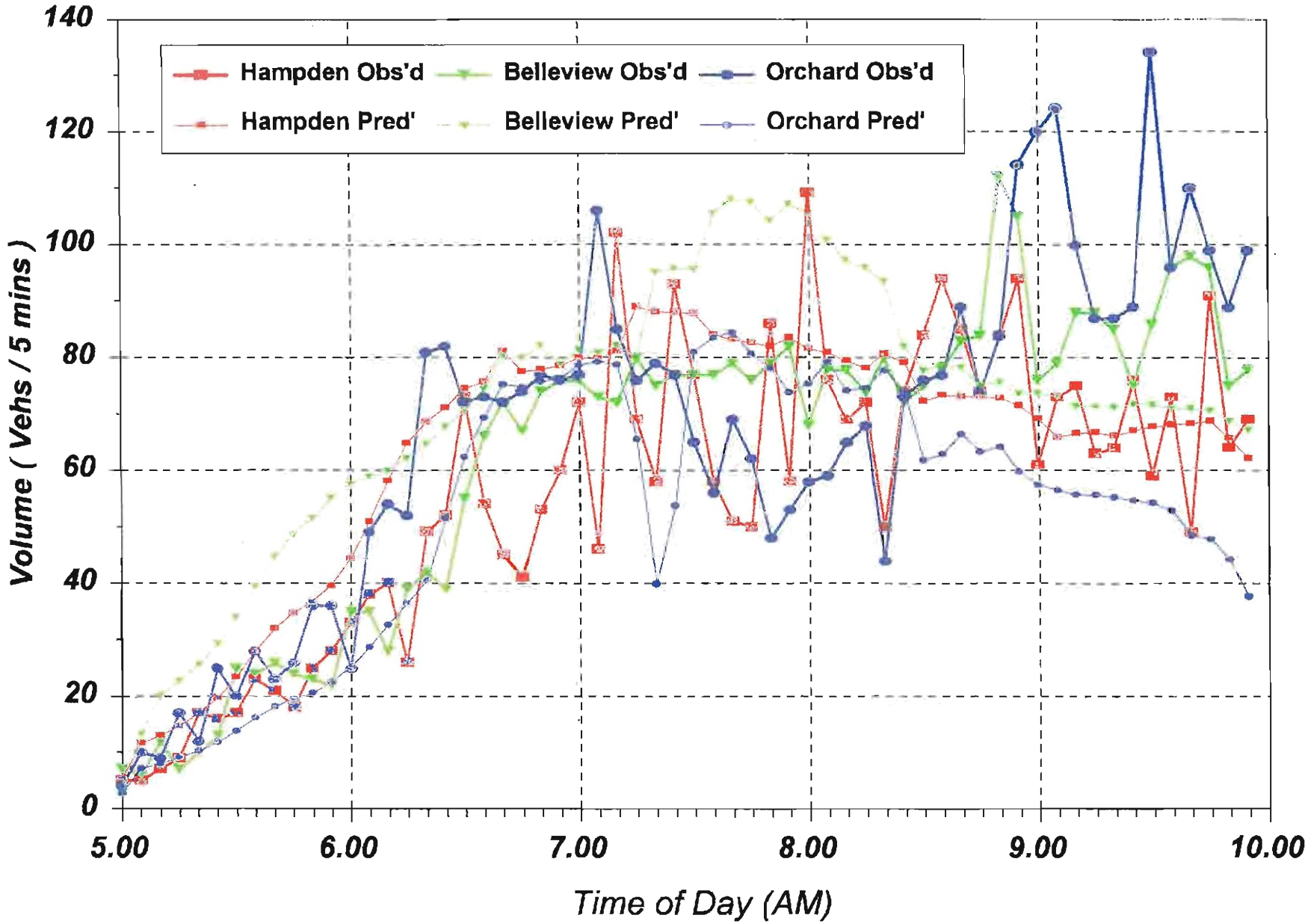

Figure 8e: Pred. vs. Obs. On-Ramp Volumes (Accident # 2)

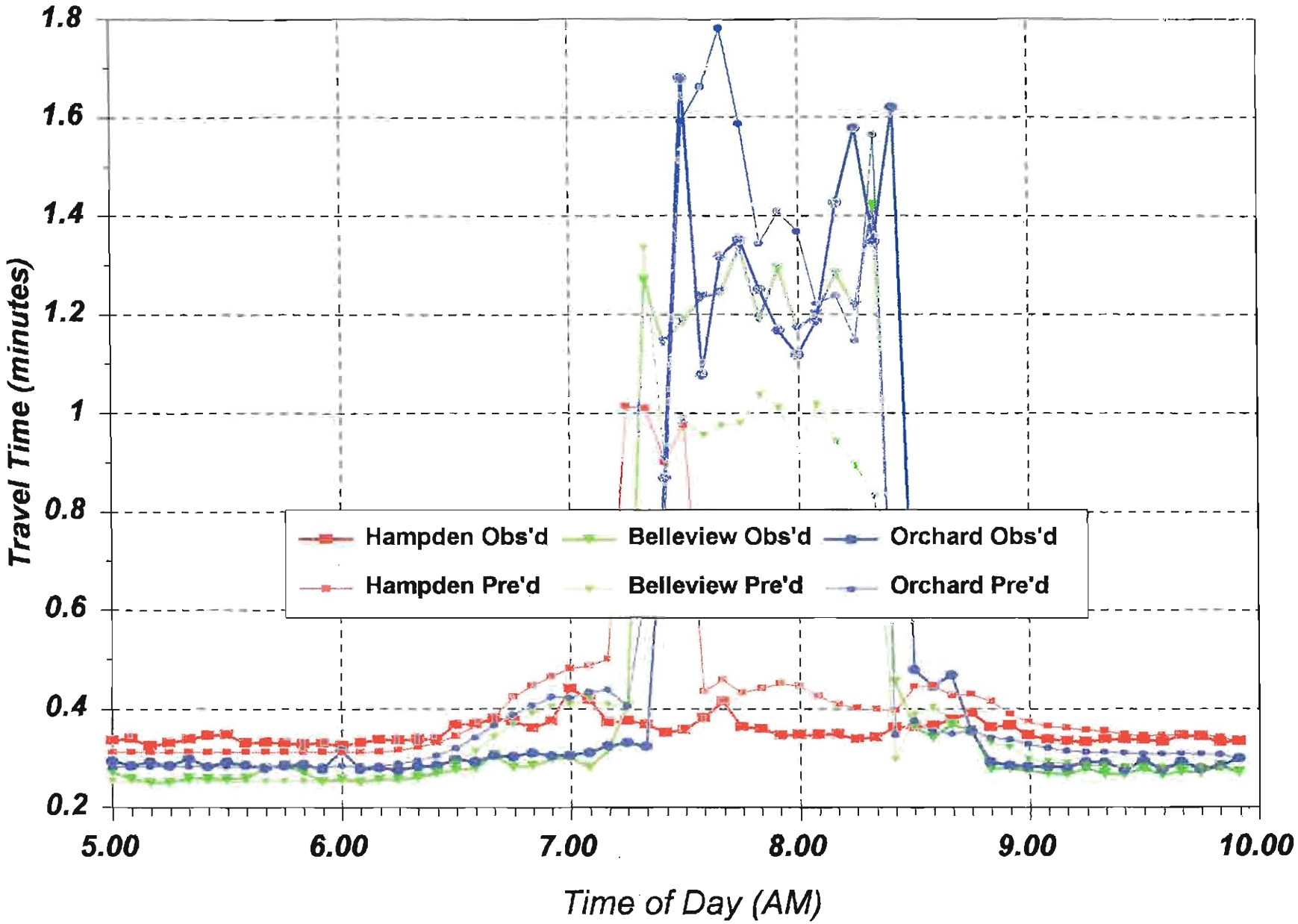

Figure 8f: Pred. vs. Obs. I-25 Times (Accident # 2)

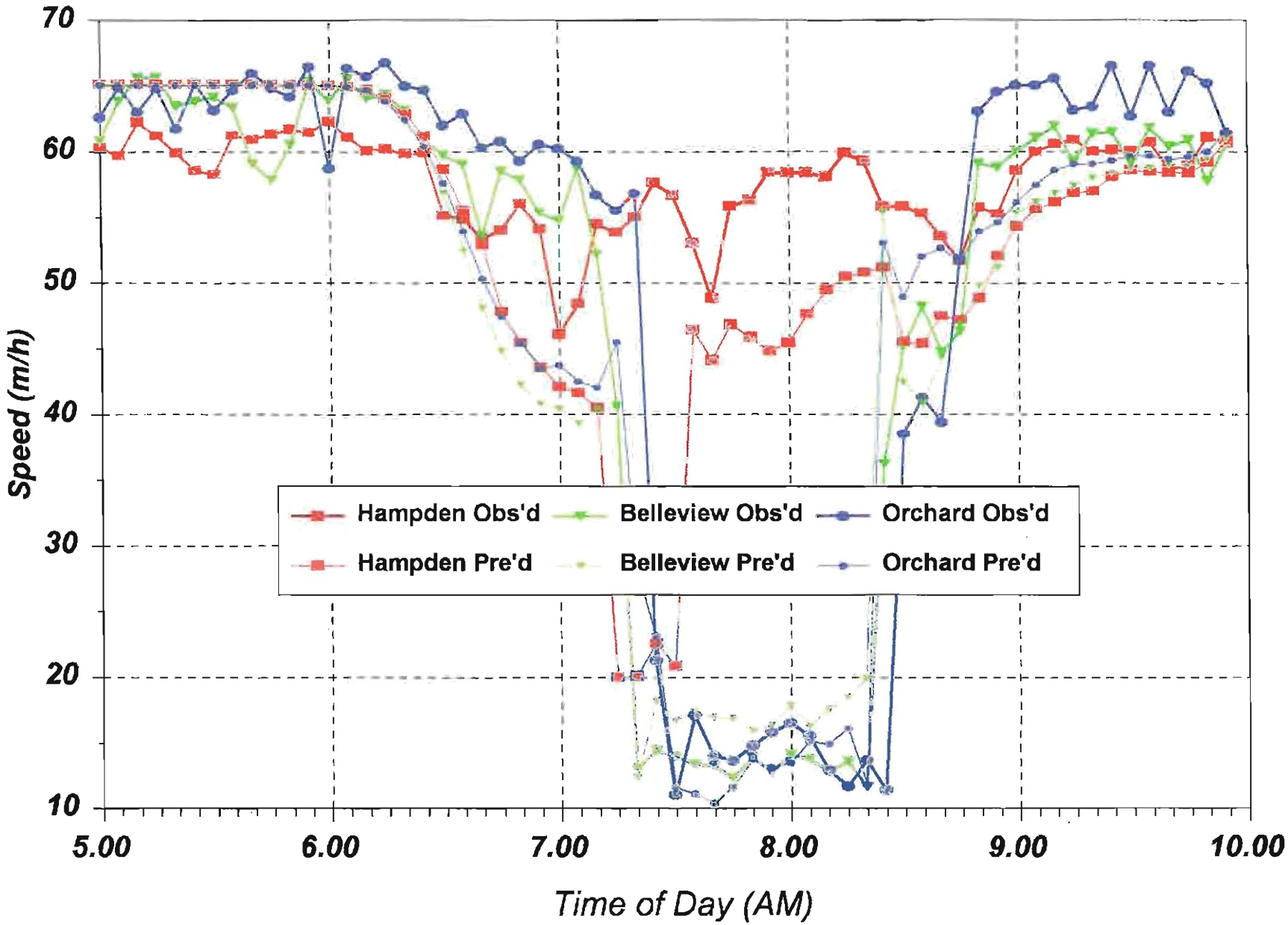

Figure 8g: Pred. vs. Obs. I-25 Speeds (Accident # 2)

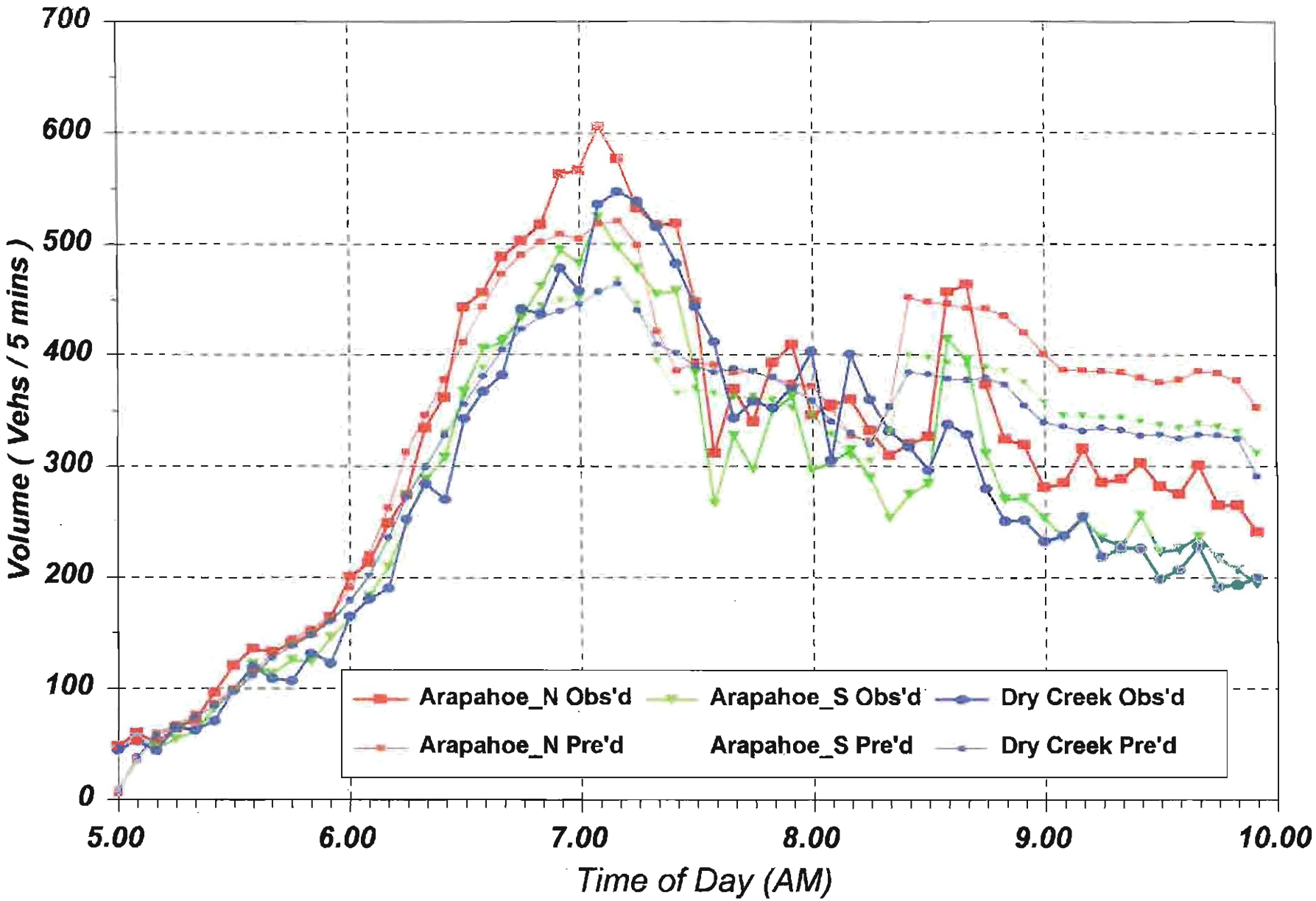

Figure 8h: Pred. vs. Obs. I-25 Upstream Volumes (Accident # 2)

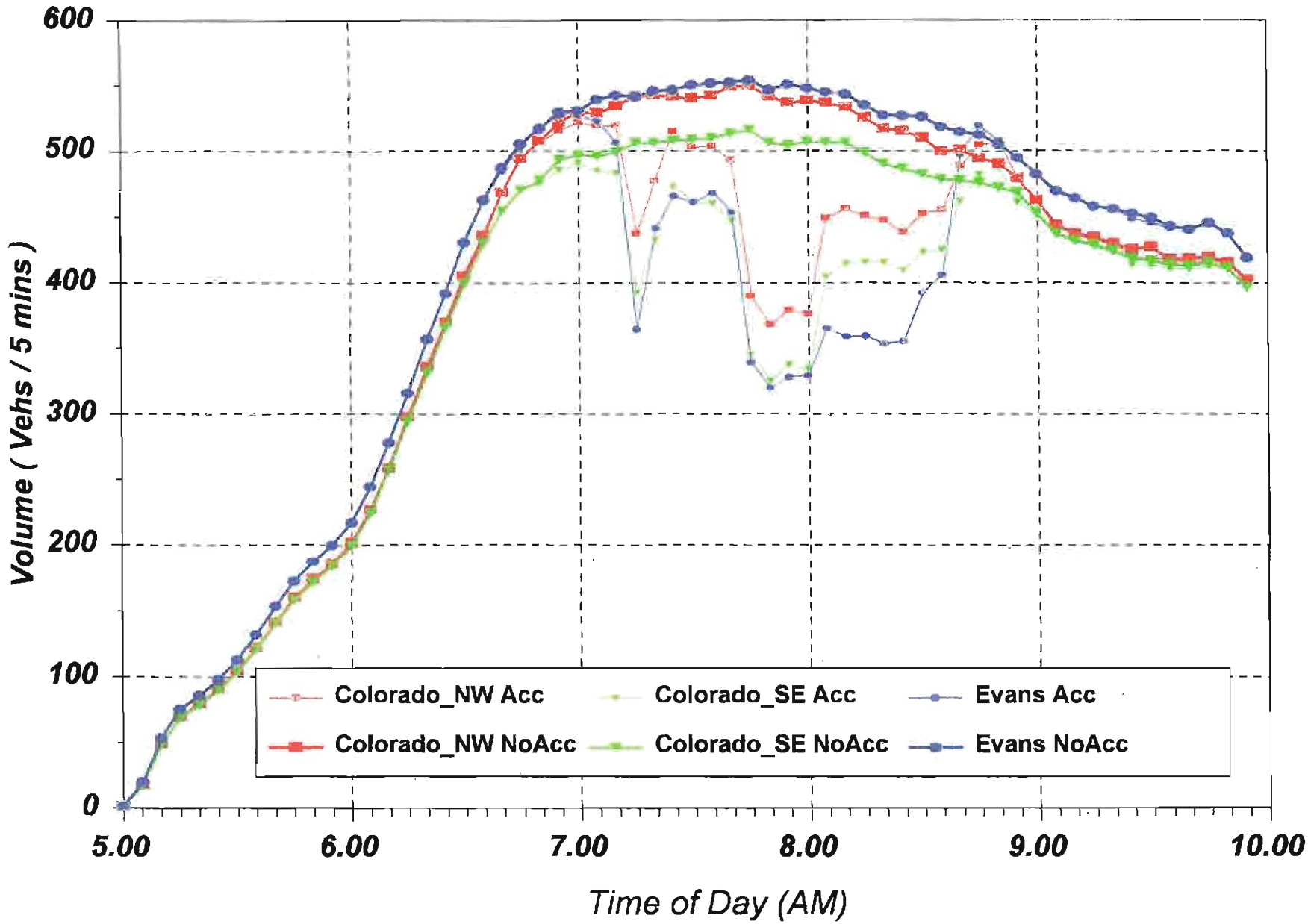

Figure 9a: Predicted I-25 Volumes (Acc. # 3 vs. No Acc.)

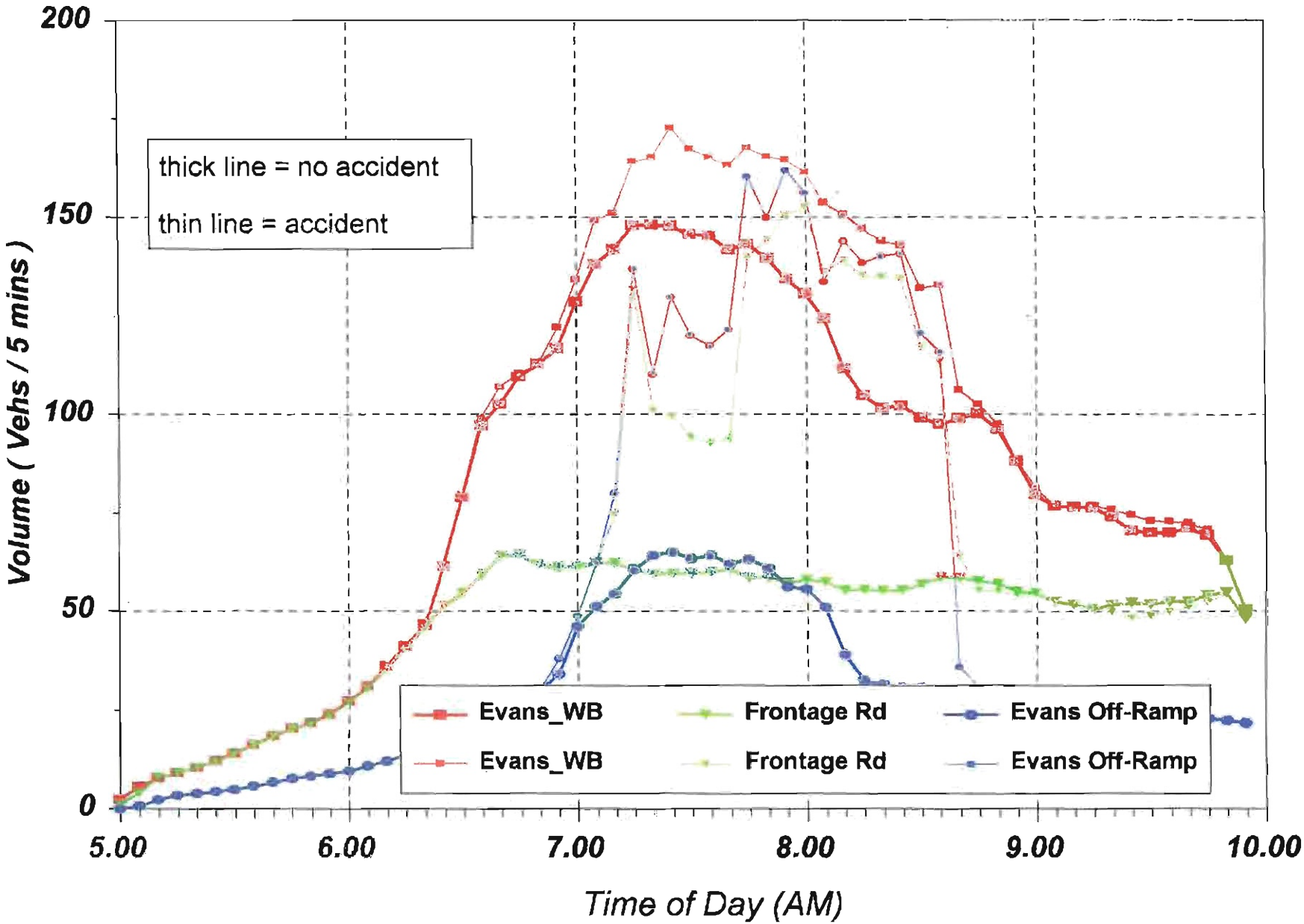

Figure 9b: Predicted Alt. Rt. Volumes (Acc. # 3 vs. No Acc.)

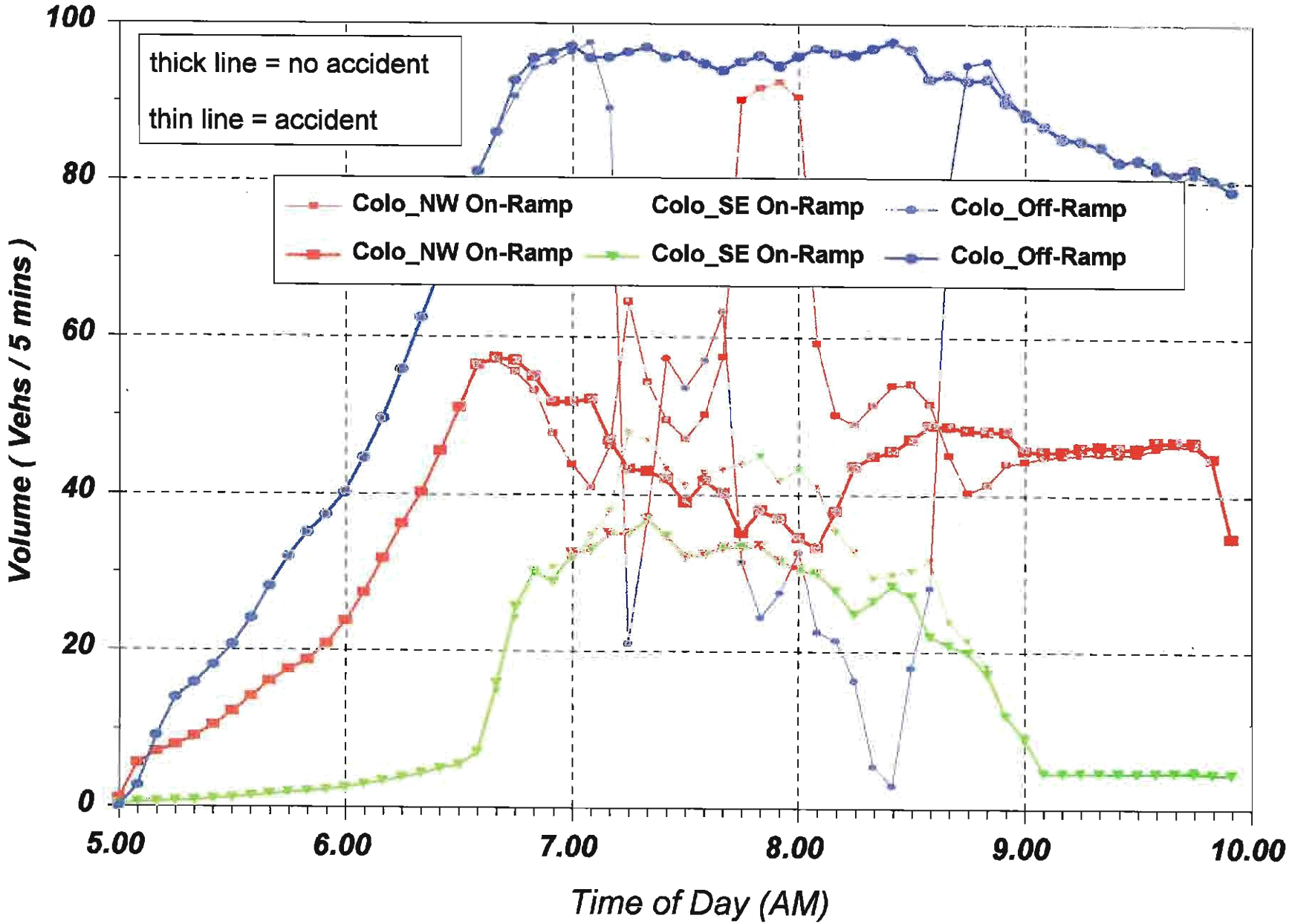

Figure 9c: Predicted Ramp Volumes (Acc. # 3 vs. No Acc.)

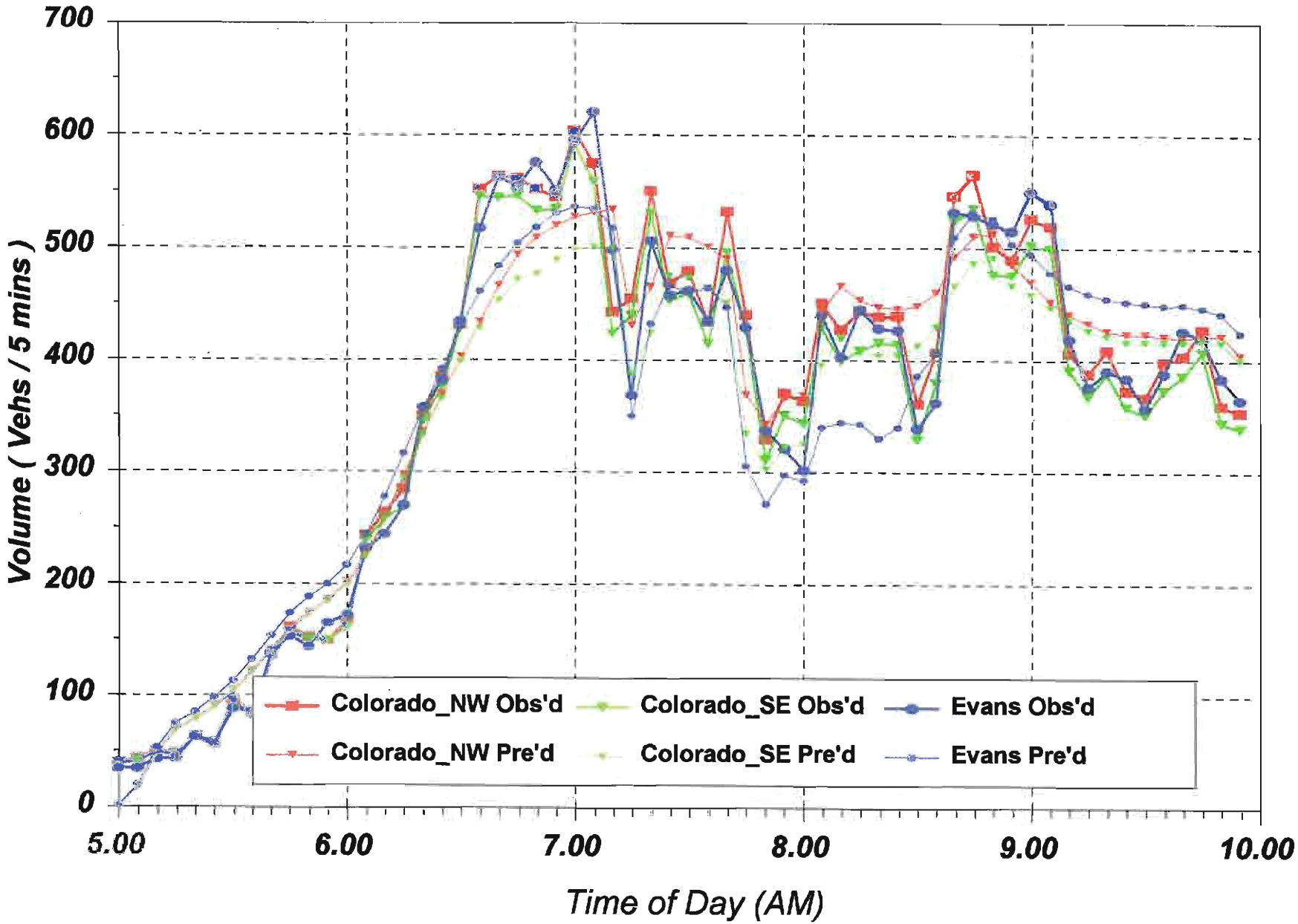

Figure 9d: Pred. vs. Obs. I-25 Volumes (Accident # 3)

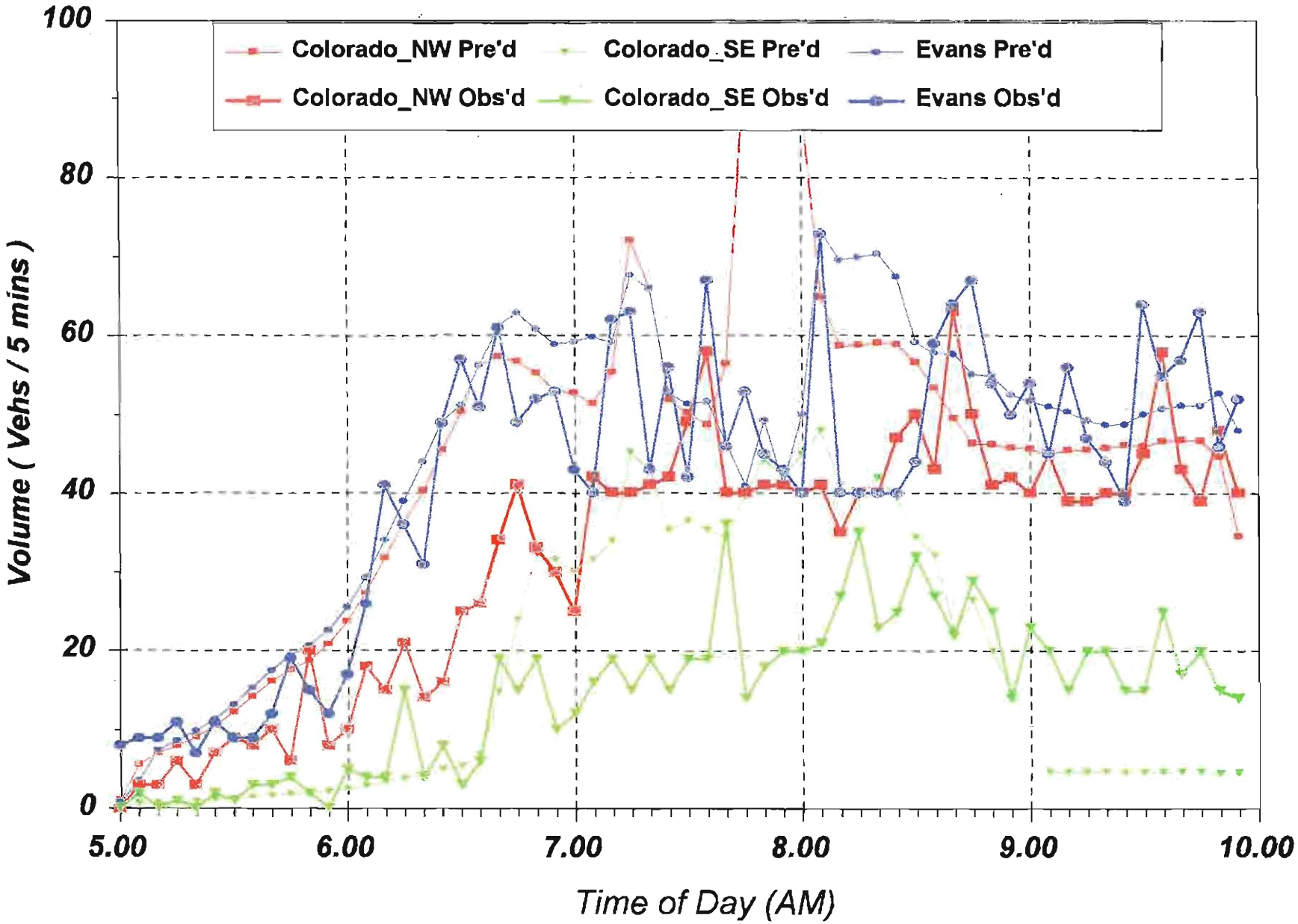

Figure 9e: Pred. vs. Obs. On-Ramp Volumes (Accident # 3)

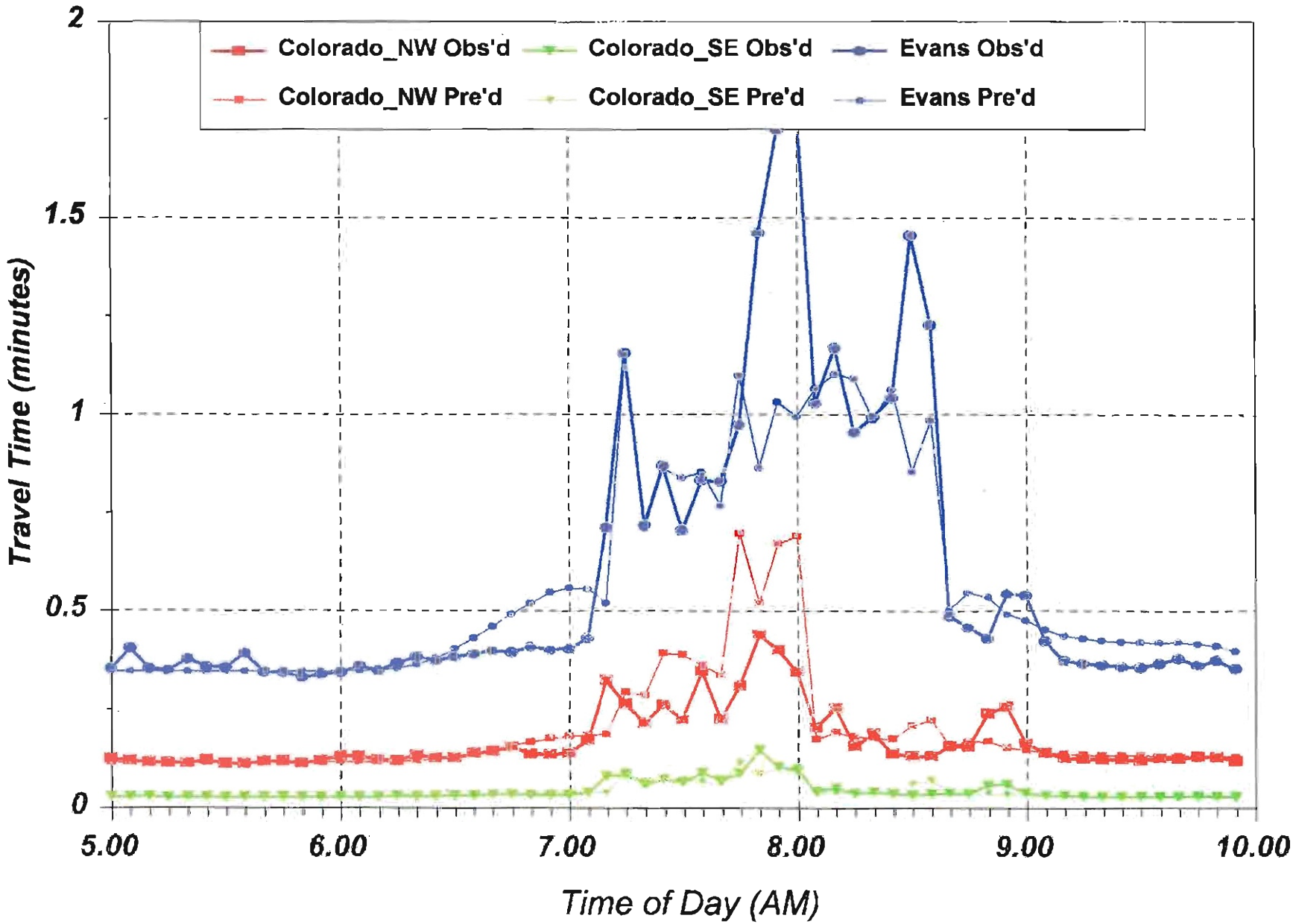

Figure 9f: Pred. vs. Obs. I-25 Times (Accident # 3)

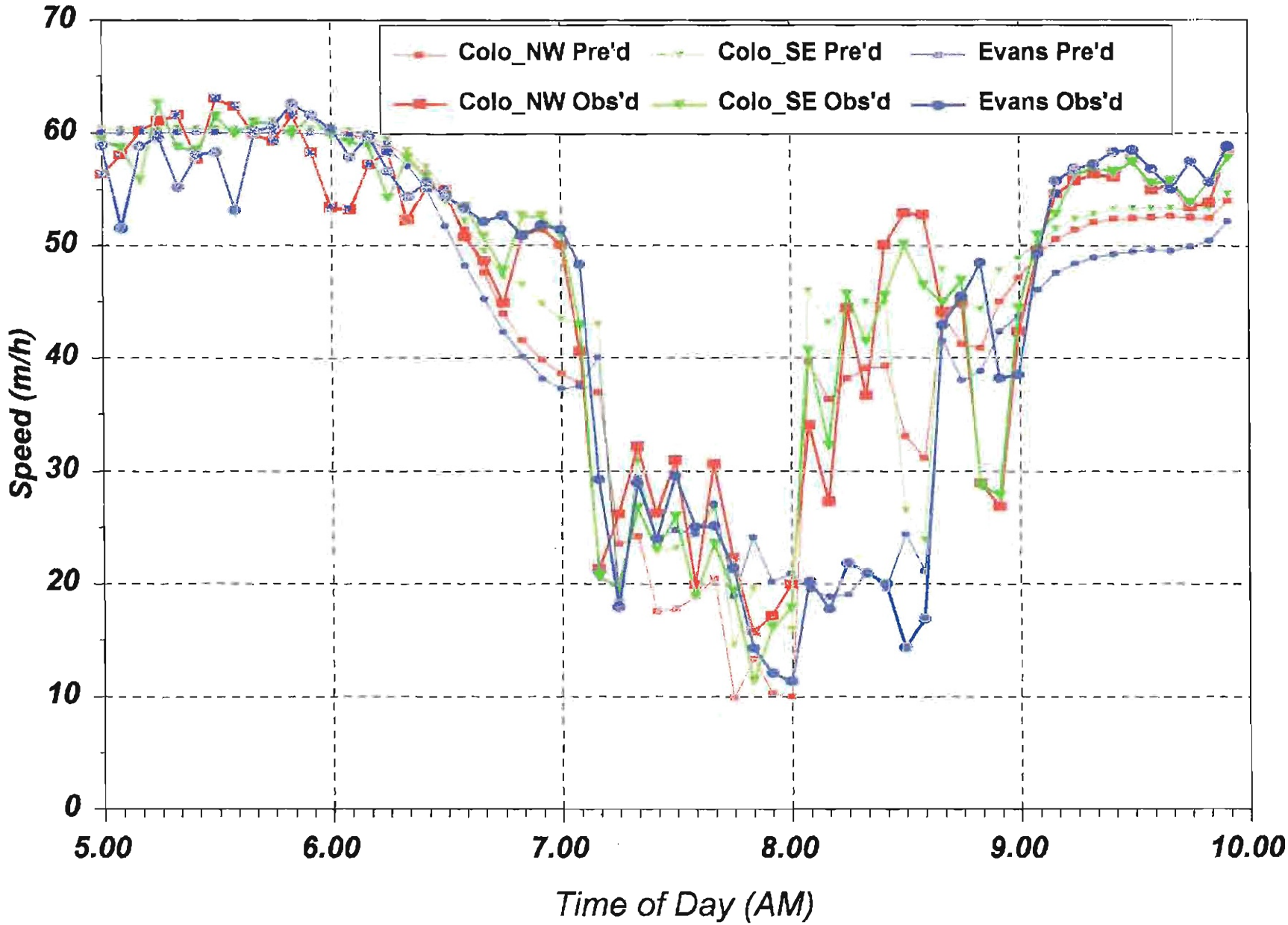

Figure 9g: Pred. vs. Obs. I-25 Speeds (Accident # 3)

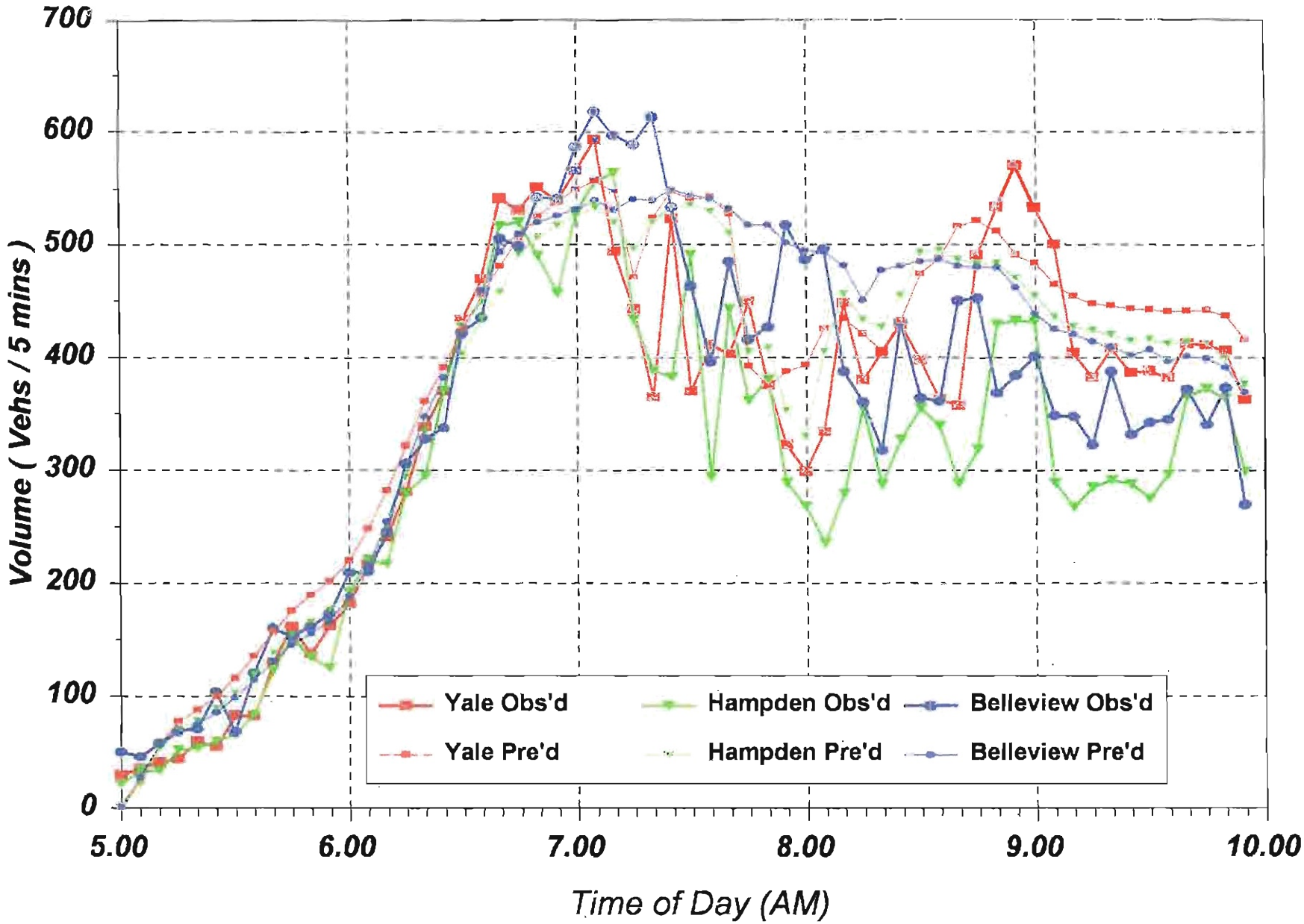

Figure 9h: Pred. vs. Obs. I-25 Upstream Volumes (Accident # 3)