



Emissions Due to Construction Equipment and Traffic Delays

Task 6: Contribution of Vehicular Emissions Caused by Reduction in Capacity during Roadway Construction

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INTRODUCTION

This task examined the impacts of shifting construction schedules in response to construction bans in Houston and Dallas with respect to emissions and delays during peak and off-peak conditions. The task proposal identified QUEWZ-98, Queue and User Cost Evaluation of Work Zones, to be selected as the modeling program to be used in performing this evaluation. During the course of the evaluation, however, researchers identified several critical limitations associated with the QUEWZ-98 model with respect to the emissions calculation algorithm. The project staff proceeded by using QUEWZ-98 for delay calculations but to develop an alternate method of modeling vehicular emissions. QUEWZ-98 directly calculated delays and road user costs associated with work zones and quantified operational characteristics of traffic flow through work zones. Traffic characteristics in the QUEWZ-98 output served as inputs to the emissions model developed in this task. This model is referred to as the Emissions Workbook and is based on Microsoft Excel® spreadsheets and Visual Basic macros.

Initially, the task sought to model actual construction projects in the Houston and Dallas areas in order to compare the emissions and delays that would be generated as a result of changing the construction schedule to accommodate construction bans in these cities. Due to limited availability of traffic control plans for existing projects, researchers modeled an array of general work zone scenarios to reflect a range of project and traffic condition intensity. Variables in the scenarios included facility demand (low, medium, and high AADT, facility cross-section (two to five lanes), number of lanes closed in work zone (one to four lanes), and work zone schedules (seven different schedules modeled). Researchers modeled five alternate work zone schedules in addition to the standard peak and off-peak direction schedules. The alternate schedules included schedules to accommodate the Dallas construction ban, the Houston construction ban, and overnight operations. The matrix created by these variables produced a total of 161 scenarios. Table 1 presents the matrix of scenarios evaluated in this task.

The remainder of this report is divided into four major sections: QUEWZ-98 Analysis, Emissions Workbook, Using the Results, and the Appendix. The QUEWZ-98 Analysis section details the range of scenarios evaluated, assumptions used, and limitations of QUEWZ-98. The Emissions Workbook section details the need for creating an alternate model for calculating emissions, the procedures to use the Emissions Workbook model developed in this task, and assumptions used in the calculations. The Using the Results section provides two examples of how the results of this study could potentially be used. Finally, the Appendix section provides a series of tables and graphs summarizing the results of the analyses of the 161 scenarios. These tables and graphs can be utilized to examine the relative impact of various construction schedules and lane closure plans for a facility with a given cross section and level of AADT.

QUEWZ-98 ANALYSIS

QUEWZ-98 is a microcomputer program developed to evaluate freeway work zone lane closures. The program simulates traffic flows through a freeway segment with and without a work zone in place. The user specifies the lane closure schedule and configuration, and the

Table 1. Matrix of Road Construction Work Zone Scenarios Modeled.

| Schedule Name | Peak Direction Scenarios | | | | Off-Peak Direction Scenarios | | | | Overnight Schedule |
|----------------|--------------------------|--------------------------------|--------------------------------|------------------|------------------------------|-----------------|------------------|------------------|--------------------|
| | Base Schedule | Dallas Schedule | Houston Schedule | Houston Schedule | Base Schedule | Dallas Schedule | Houston Schedule | Houston Schedule | |
| Schedule Hours | 09:00 - 17:00 | 10:00 - 15:00 19:00 - 22:00 | 12:00 - 15:00 19:00 - 24:00 | 07:00 - 15:00 | 10:00 - 18:00 | 12:00 - 20:00 | 21:00 - 05:00 | | |
| Low AADT | 1 of 2 closed | 1 of 2 closed | 1 of 2 closed | 1 of 2 closed | 1 of 2 closed | 1 of 2 closed | 1 of 2 closed | 1 of 2 closed | |
| | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | |
| | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | |
| | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | |
| | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | |
| | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | |
| | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | |
| | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | |
| Medium AADT | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | |
| | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | |
| | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | 1 of 3 closed | |
| | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | 2 of 3 closed | |
| | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | 1 of 4 closed | |
| | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | 2 of 4 closed | |
| | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | 3 of 4 closed | |
| | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | |
| High AADT | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | |
| | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | |
| | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | |
| | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | |
| | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | 2 of 5 closed | |
| | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | 3 of 5 closed | |
| | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | 4 of 5 closed | |
| | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | 1 of 5 closed | |

program outputs the resulting impact of the work zone with respect to road user costs, queues, and emissions. QUEWZ-98 can also be used to identify lane closure schedules that minimize work zone related delay. The model can analyze 24 consecutive hours of operation on freeways/multi-lane divided highways with up to six lanes in each direction and work zones in one or both directions.

QUEWZ-98 INPUT DATA

The input data required to set up a QUEWZ-98 simulation file include data on the lane closure configuration and schedule, traffic volumes approaching the freeway segment, and adjustments to model defaults.

Lane Closure Configuration

Lane closure configuration data include the number of directional roadways closed (one or both directions), the total number of lanes in each direction, the number of lanes open in each direction through the work zone, the length of the lane closure, and the capacity of the work zone. The assumptions used in simulations created for this task include:

- work zone on one side of the freeway only,
- number of lanes in the freeway segment varied between two and five,
- number of lanes closed in work zone varied between one and four lanes, and
- length of work zone equal to one mile.

Lane Closure Schedule

Lane closure schedule data include the hours the lane closure begins and ends and the hours work activity begins and ends. It was assumed in these simulations that lane closure and work activity times coincided. Table 2 presents the seven construction schedules evaluated in this task. Two base condition schedules simulated typical construction schedules, 09:00 – 17:00 when the work zone is located in the AM peak direction of flow, or 07:00 – 15:00 when the work zone is located in the AM off-peak direction of flow. These schedules are derived from current practices which prohibit lane closures in the peak direction of travel during the peak period. Peak and off-peak Dallas schedules simulated the impact of the proposed construction ban in Dallas, which would ban heavy-duty diesel construction activity prior to 10:00. Peak and off-peak Houston schedules simulate the impact of the proposed construction ban in Houston, which would ban heavy-duty diesel construction activity prior to 12:00. The final construction schedule simulated overnight work.

Traffic Volumes

The Texas Department of Transportation (TxDOT) provided researchers with 1999 Harris County freeway and interstate AADTs. Researchers ranked the AADTs from highest to lowest and selected three levels of AADT to simulate roadways with low, medium, and high traffic volumes. The 85th percentile AADT represents high demand facilities and corresponds to 180,000 vehicles per day. The 50th percentile AADT represents medium demand facilities and

Table 2. Construction Schedules Simulated in Evaluation.

| Schedule Name | Direction of Flow | Lane Closure Schedule |
|---------------|-----------------------|------------------------------|
| Base | AM Peak Direction | 09:00 – 17:00 |
| | AM Off-Peak Direction | 07:00 – 15:00 |
| Dallas | PM Peak Direction | 10:00 – 15:00, 19:00 – 22:00 |
| | PM Off-Peak Direction | 10:00 – 18:00 |
| Houston | PM Peak Direction | 12:00 – 15:00, 19:00 – 24:00 |
| | PM Off-Peak Direction | 12:00 – 20:00 |
| Overnight | Off-Peak Direction | 21:00 – 05:00 |

corresponds to 110,000 vehicles per day. The 30th percentile AADT represents low demand facilities and corresponds to 56,000 vehicles per day. QUEWZ-98 distributes the AADT value for a 24-hour period using adjustment factors to account for rural/urban environment and day of week (weekday, Saturday, or Sunday). These adjustment factors were computed at the time QUEWZ-98 was developed based on automatic traffic recorder station data on interstate highways in Texas in October 1985 (37 urban stations and 13 rural stations) (1).

Adjustments to Model Defaults

The final input values are user-specified alternatives to default values of:

- cost update factor,
- percent trucks,
- speed-volume-capacity relationships,
- work zone capacity,
- definition of excessive queuing, and
- emission rates.

All simulations used a cost update factor of 1.3. This factor converts road user costs to year 2000 dollars (current year consumer price index [CPI] divided by year 1990 consumer price index of 130.7). The default value in QUEWZ-98 for percentage of trucks in the traffic stream is 8 percent. The AADT data from TxDOT revealed an average percentage of trucks on Harris County freeways and interstates of 7.9 percent, justifying the model default of 8 percent. The default speed-volume-capacity relationships in QUEWZ-98 are based on the 1985 *Highway Capacity Manual*. These default values were used in all simulations. The ideal capacity of a work zone is assumed by QUEWZ-98 to be 1600 vehicles per hour per lane (vphpl). This capacity reduced to 1515 vphpl when factoring in an adjustment for heavy vehicles and was used in all simulations.

The definition of excessive queuing is an option in QUEWZ-98 to allow for the diversion of vehicles within the simulation. Excessive queuing can be defined as a maximum queue length in miles or a maximum delay in minutes. QUEWZ-98 uses the diversion algorithm to calculate the diversion volume to avoid excessive queuing. The default value for the critical length of queue is two miles, based on average ramp spacing of 0.4 miles, and a maximum of five ramps being engulfed in the queue. These averages are based on diversion studies at temporary

freeway work zone lane closures on urban freeways with continuous frontage roads in Texas (1). The diversion algorithm engaged in all simulations when a critical length of queue exceeded two miles.

Analyses used the default pollutant emission rates contained in QUEWZ-98 for car and truck hydrocarbon, nitrous oxide, and carbon monoxide. These values were estimated in the summer of 1998 using data from San Antonio, Texas, and the emissions modeling program Mobile Source Emission Factor Model (MOBILE5a) (2). See the Limitations of the QUEWZ-98 Model section for more information on emission calculations.

QUEWZ-98 OUTPUT DATA

A QUEWZ-98 output file consists of three to four pages of data depending on the geometrics and/or traffic volumes in the scenario. Page one of the output file provides an echo of some of the input data, as shown in Figure 1. These data include the number of lanes in the section, number of lanes closed, length of work zone, normal and restricted capacities, AADT, parameters used to calculate hourly volumes from the AADT (weekday and urban environment adjustment factors engaged), scheduled hours of the work zone, and idle emission rates for hydrocarbon HC, CO, and NOx.

The second page of the QUEWZ-98 output file contains the road user cost table shown in Figure 2. Road user costs are shown on an hourly basis and totaled at the bottom of the table. Road user costs are estimated for a work zone by taking the difference between road user costs with and without the work zone in place. The road user cost includes a vehicle operating cost component and a travel time cost component. The value of time assumed by QUEWZ-98, based on 1990 dollars, is \$12.64 per hour for passenger cars (average occupancy 1.3 persons per vehicle) and \$23.09 per hour for trucks (1). This value of time was updated to 2000 dollars using a cost update factor of 1.3 (CPI year 2000 divided by CPI year 1990).

Total road user cost calculations include road user costs for diverting vehicles in the event of vehicle diversion by the excessive queuing algorithm. The assumptions built into QUEWZ-98 for vehicle diversion are:

- the length of the alternate route equals the length of the work zone plus the critical length of queue,
- the travel time for diverting vehicles is equal to the time required for a vehicle at the end of the queue to travel through the queue and work zone,
- diverting traffic maintains a uniform speed equal to the length of the alternative route divided by the travel time, and
- trucks do not divert.

Page three of the output file, shown in Figure 3, provides a summary of hourly traffic flow characteristics. Traffic conditions reported on an hourly basis include the approach volume, work zone capacity, approach speed, work zone speed, and length of queue. This page provides the majority of input data for the Emissions Workbook. Although QUEWZ-98 distributes

LANE CLOSURE CONFIGURATION:

| | |
|-----------------------|--------------|
| TOTAL NUMBER OF LANES | |
| INBOUND | 5 |
| OUTBOUND | 5 |
| NUMBER OF OPEN LANES | |
| INBOUND | 3 |
| OUTBOUND | 5 |
| LENGTH OF WORK ZONE | 1.00 MILES |
| INBOUND CAPACITY | |
| NORMAL | 10000. (VPH) |
| RESTRICTED | 5400. (VPH) |
| WORKING HOURS | 4545. (VPH) |

TRAFFIC PARAMETERS:

| | |
|-------------------------|----------|
| PARAMETERS TO CALCULATE | |
| HOURLY TRAFFIC VOLUMES | |
| DAY OF WEEK | MONDAY |
| MONTH | OCTOBER |
| DISTRICT | 99 |
| LOCATION | URBAN IN |
| AADT (THOUS.) | 180.0 |
| PERCENTAGE TRUCK | 8. |

SCHEDULE OF WORK ACTIVITY:

| | |
|------------------------------|----|
| HOURS OF RESTRICTED CAPACITY | |
| BEGINNING | 10 |
| ENDING | 15 |
| HOURS OF WORK ZONE ACTIVITY | |
| BEGINNING | 10 |
| ENDING | 15 |

| | | | |
|--------------|--------------|----------------|-------------|
| IDLE HC CAR | 34.9 (g/hr) | IDLE HC TRUCK | 12.6 (g/hr) |
| IDLE CO CAR | 218.5 (g/hr) | IDLE CO TRUCK | 94.6 (g/hr) |
| IDLE NOX CAR | 4.7 (g/hr) | IDLE NOX TRUCK | 53.1 (g/hr) |

Figure 1. Input Echo - Page 1 of QUEWZ-98 Output File.

| ----- | | | |
|---------------------------------|---------|----------|--------|
| ADDITIONAL ROAD USER COSTS (\$) | | | |
| HOUR | INBOUND | OUTBOUND | TOTAL |
| ----- | | | |
| 0- 1 | 0. | 0. | 0 |
| 1- 2 | 0. | 0. | 0. |
| 2- 3 | 0. | 0. | 0. |
| 3- 4 | 0. | 0. | 0. |
| 4- 5 | 0. | 0. | 0. |
| 5- 6 | 0. | 0. | 0. |
| 6- 7 | 0. | 0. | 0. |
| 7- 8 | 0. | 0. | 0. |
| 8- 9 | 0. | 0. | 0. |
| 9-10 | 0. | 0. | 0. |
| 10-11 | 5522. | 0. | 5522. |
| 11-12 | 11660. | 0. | 11660. |
| 12-13 | 19516. | 0. | 19516. |
| 13-14 | 26893. | 0. | 26893. |
| 14-15 | 30297. | 0. | 30297. |
| 15-16 | 4378. | 0. | 4378. |
| 16-17 | 0. | 0. | 0. |
| 17-18 | 0. | 0. | 0. |
| 18-19 | 0. | 0. | 0. |
| 19-20 | 0. | 0. | 0. |
| 20-21 | 0. | 0. | 0. |
| 21-22 | 0. | 0. | 0. |
| 22-23 | 0. | 0. | 0. |
| 23-24 | 0. | 0. | 0. |
| ----- | | | |
| TOTAL | 98267. | 0. | 98267 |
| ----- | | | |

NOTE: LANE CLOSURE ONLY IN INBOUND DIRECTION

Figure 2. Road User Costs - Page 2 of QUEWZ-98 Output File.

| HOUR | APPROACH VOLUME (VPH) | CAPACITY (VPH) | APPROACH SPEED (MPH) | WORK ZONE SPEED (MPH) | QUEUE LENGTH (MILES) |
|-------|-----------------------------|-------------------|----------------------------|-----------------------------|----------------------------|
| 0- 1 | | | | | |
| 1- 2 | | | | | |
| 2- 3 | | | | | |
| 3- 4 | | | | | |
| 4- 5 | | | | | |
| 5- 6 | | | | | |
| 6- 7 | | | | | |
| 7- 8 | | | | | |
| 8- 9 | | | | | |
| 9-10 | | | | | |
| 10-11 | 4820. | 4545. | 53. | 30. | 0.2 |
| 11-12 | 4923. | 4545. | 53. | 30. | 0.7 |
| 12-13 | 5004. | 4545. | 52. | 30. | 1.3 |
| 13-14 | 5076. | 4545. | 52. | 30. | 1.8 |
| 14-15 | 5204. | 4545. | 52. | 30. | 2.0 |
| 15-16 | 5639. | 10000. | 51. | 45. | 1.0 |
| 16-17 | | | | | |
| 17-18 | | | | | |
| 18-19 | | | | | |
| 19-20 | | | | | |
| 20-21 | | | | | |
| 21-22 | | | | | |
| 22-23 | | | | | |
| 23-24 | | | | | |

NOTE: TRAFFIC DIVERSION IS PREDICTED, SEE SUMMARY OF TRAFFIC VOLUMES

Figure 3. Summary of Traffic Conditions - Page 3 of QUEWZ-98 Output File.

AADT over the full 24-hour period, the output reflects only data during the time period in which the work zone is in place. This limited time period is due to the intended use of QUEWZ-98 to determine the differences between delay and emissions when a work zone is and is not in place. Since there is no differential delay or emissions during periods of time when the work zone is not in place, QUEWZ-98 omits those data from the output file. The only exception is when a queue exists at the end of the work zone schedule, in which case QUEWZ-98 will continue the simulation until the queue is dissipated.

Page four of the QUEWZ-98 output file is shown in Figure 4. This page provides a table summarizing hourly diversion volumes for time periods where the queue reaches the critical queue length of two miles (queue length shown on page three of output file). A summary of emissions calculations follows the diversion summary on page four of the output file.

LIMITATIONS OF THE QUEWZ-98 MODEL

The researchers identified a number of limitations with the QUEWZ-98 model during its application in this task. To some extent the model was not designed to handle some of the aspects of this evaluation. The primary limitations of the QUEWZ-98 model for this task concern the emissions algorithm. QUEWZ-98 has an algorithm to estimate the number of vehicles that would divert from a work zone facility once a critical length of queue or a critical delay in queue is reached. While QUEWZ-98 includes the delays associated with diverting vehicles in its road user cost algorithm, it ignores all emissions associated with diverting vehicles. Thus, QUEWZ-98 would underestimate the emissions associated with work zones on high-volume facilities or during high-volume time periods, where vehicular diversion would be expected to occur.

In some of the scenarios, the work zone had enough impact to cause a reduction in vehicle speeds but did not have a large enough impact to cause queue formation. As long as there is no queue associated with a work zone, QUEWZ-98 ignores emissions of all vehicles traveling through the work zone regardless of their speed. Thus, QUEWZ-98 underestimates HC and CO, and overestimates NO_x when vehicle speeds are reduced due to a work zone, but no queue is formed.

The Dallas peak and Houston peak schedule scenarios modeled construction work zones set up before a peak period, removed during the peak period, then reestablished after the peak period. One limitation of QUEWZ-98 is that only a single work zone closure can be simulated during a 24-hour period. In order to simulate two work zone closures during a 24-hour period, two QUEWZ-98 files needed to be created. Each file contained 12 hours of volumes and one work zone closure, i.e., creating two separate files did not double the 24-hour volume. Combining the two output files then produced the results for those scenarios.

Volume data are entered in QUEWZ-98 for a 24-hour period beginning at 00:00 and ending at 23:00. Simulating an overnight schedule such as 21:00 to 05:00 would either require creating two files, one to contain the 21:00 to midnight portion and another to contain the midnight to 05:00 portion, or simply shifting the volumes and corresponding times. Shifting the volume data 20 hours (such that 20:00 corresponded with 00:00 in QUEWZ-98) allowed a single file to be used.

| HOUR | APPROACH VOLUME (VPH) | VOLUME REMAINING ON FREEWAY (VPH) | VOLUME DIVERTING FROM FREEWAY (VPH) |
|-------|-----------------------------|---|---|
| 0- 1 | 890. | 890. | 0. |
| 1- 2 | 600. | 600. | 0. |
| 2- 3 | 512. | 512. | 0. |
| 3- 4 | 468. | 468. | 0. |
| 4- 5 | 683. | 683. | 0. |
| 5- 6 | 1836. | 1836. | 0. |
| 6- 7 | 6209. | 6209. | 0. |
| 7- 8 | 8993. | 8993. | 0. |
| 8- 9 | 6629. | 6629. | 0. |
| 9-10 | 5161. | 5161. | 0. |
| 10-11 | 4820. | 4820. | 0. |
| 11-12 | 4923. | 4923. | 0. |
| 12-13 | 5004. | 5004. | 0. |
| 13-14 | 5076. | 4754. | 323. |
| 14-15 | 5204. | 4545. | 659. |
| 15-16 | 5639. | 5639. | 0. |
| 16-17 | 6093. | 6093. | 0. |
| 17-18 | 5868. | 5868. | 0. |
| 18-19 | 4435. | 4435. | 0. |
| 19-20 | 3221. | 3221. | 0. |
| 20-21 | 2341. | 2341. | 0. |
| 21-22 | 2049. | 2049. | 0. |
| 22-23 | 1709. | 1709. | 0. |
| 23-24 | 1183. | 1183. | 0. |

NOTE: THESE ESTIMATES ASSUME THAT TRAFFIC WILL DIVERT SUCH THAT
 QUEUE LENGTHS NEVER EXCEED 2.00 MILES.

| EXCESS EMISSIONS (DIFFERENCE) | | | |
|--------------------------------|-------------|-------------|--------------|
| | HC (Kgs) | CO (Kgs) | NOx (Kgs) |
| Inbound | 102.2 | 700.4 | -73.0 |
| Outbound | 0.0 | 0.0 | 0.0 |
| BASE EMISSIONS | | | |
| | HC (Kgs) | CO (Kgs) | NOx (Kgs) |
| Inbound | 89.4 | 515.8 | 187.1 |
| Outbound | 0.0 | 0.0 | 0.0 |
| CONSTRUCTION RELATED EMISSIONS | | | |
| | HC (Kgs) | CO (Kgs) | NOx (Kgs) |
| Inbound | 191.6 | 1216.2 | 114.0 |
| Outbound | 0.0 | 0.0 | 0.0 |

Figure 4. Diversion and Emissions Summary - Page 4 of QUEWZ-98 Output File.

Another limitation of the QUEWZ-98 model concerns the inability to see a complete echo of the coded input. Volumes are entered in QUEWZ-98 by entering an AADT value (which is automatically distributed by QUEWZ-98) or by manually entering hourly data. Applying the same directional and hourly distribution factors as QUEWZ-98 allowed researchers to calculate the hourly volumes from the AADT. This had to be done for the overnight scenario files where the hourly volumes needed to be shifted and for the Houston and Dallas peak direction schedules where two files needed to be created (each with 12 hours of hourly volumes). While the output file echoes the AADT used in the simulation, only those hourly volumes where the work zone is present or residual queues exist are echoed. Although the manually entered volumes could be verified on screen with the file open in QUEWZ-98, error checking manually entered volumes would be easier if echoed in the output file.

EMISSIONS WORKBOOK

After reviewing the output from the QUEWZ-98 model, researchers determined that the model did not fully describe the emissions generated from work zone lane closures. Results identified two important limitations of the QUEWZ-98 emissions algorithm. The first limitation is associated with diverting vehicles. QUEWZ-98 has an algorithm to estimate the number of vehicles that would divert from a work zone facility once a critical length of queue or a critical delay in queue is reached. QUEWZ-98 includes the delays associated with diverting vehicles in its road user cost algorithm, however, it ignores all emissions associated with diverting vehicles. Thus, QUEWZ-98 would underestimate the emissions associated with work zones on high-volume facilities or during high-volume time periods, where vehicular diversion would be expected to occur.

The second limitation is associated with conditions where a work zone has enough impact to cause a reduction in vehicle speeds but does not have a large enough impact to cause queue formation. As long as there is no queue associated with a work zone, QUEWZ-98 ignores emissions of all vehicles traveling through the work zone regardless of their speed. Thus, QUEWZ-98 underestimates VOC and CO, and overestimates NO_x, when vehicle speeds are reduced due to a work zone but no queue is formed.

PROCEDURE FOR USING THE EMISSIONS WORKBOOK

A separate model called the Emissions Workbook was developed to address the limitations associated with the QUEWZ-98 emissions algorithm and more accurately quantify emissions associated with construction work zones. The Emissions Workbook is a Microsoft Excel workbook containing a number of spreadsheets and Visual Basic macros. The sheets contained in the Emissions Workbook are the:

- Instruction Sheet,
- Paste Sheet,
- QUEWZ-98 Intermediate Calculations Sheet,
- Emission Calculations Sheet,
- MOBILE5a Emissions Table Sheet,

- percent AADT table sheet, and
- graphics sheet.

Although QUEWZ-98 was not used directly to calculate vehicle emissions for the various geometric and volume scenarios described in Table 1, it was used as a preprocessor to generate input values for the Emissions Workbook. Traffic flow characteristics utilized from QUEWZ-98 output include approach volume, approach speed, work zone speed, queue length, and diverting volumes. MOBILE5a freeway and arterial look-up tables provided the emission rates needed for the Emissions Workbook (2).

The following sections describe the process used to calculate vehicle emissions and are based on the sheets contained in the Emissions Workbook. The output files from the QUEWZ-98 simulations serve as the input to the Emissions Workbook. In most cases, the entire output file is cut and pasted into the paste sheet section. The rest of the calculations and graphs are done automatically. Figure 5 shows the data flow from the QUEWZ-98 model and through the series of spreadsheets in the workbook. This information serves as documentation of the logic and assumptions used in the emissions calculations.

Instruction Sheet

This sheet gives general instructions on how to copy and paste information from the QUEWZ-98 output file to the Emissions Workbook.

Paste Sheet

The output from the QUEWZ-98 model serves as input to the emissions calculations. The paste sheet is the location where the QUEWZ-98 output is entered into the Emissions Worksheet. For the majority of the scenarios evaluated (base peak, base off-peak, Dallas off-peak, and Houston off-peak), the entire QUEWZ-98 output file can be cut and pasted into the Emissions Workbook. The process is completed using the following steps:

1. Open Microsoft Excel and then open the desired QUEWZ-98 output file.
2. Import the output from QUEWZ-98 into Excel and parse the file using the delimited radio button and check the tab and space boxes. Click Next and then Finish.
3. Highlight the entire sheet (an easy way to do this is to start in cell A1 and then press the Shift, Ctrl, and End keys). Copy the selection by using Ctrl+C.

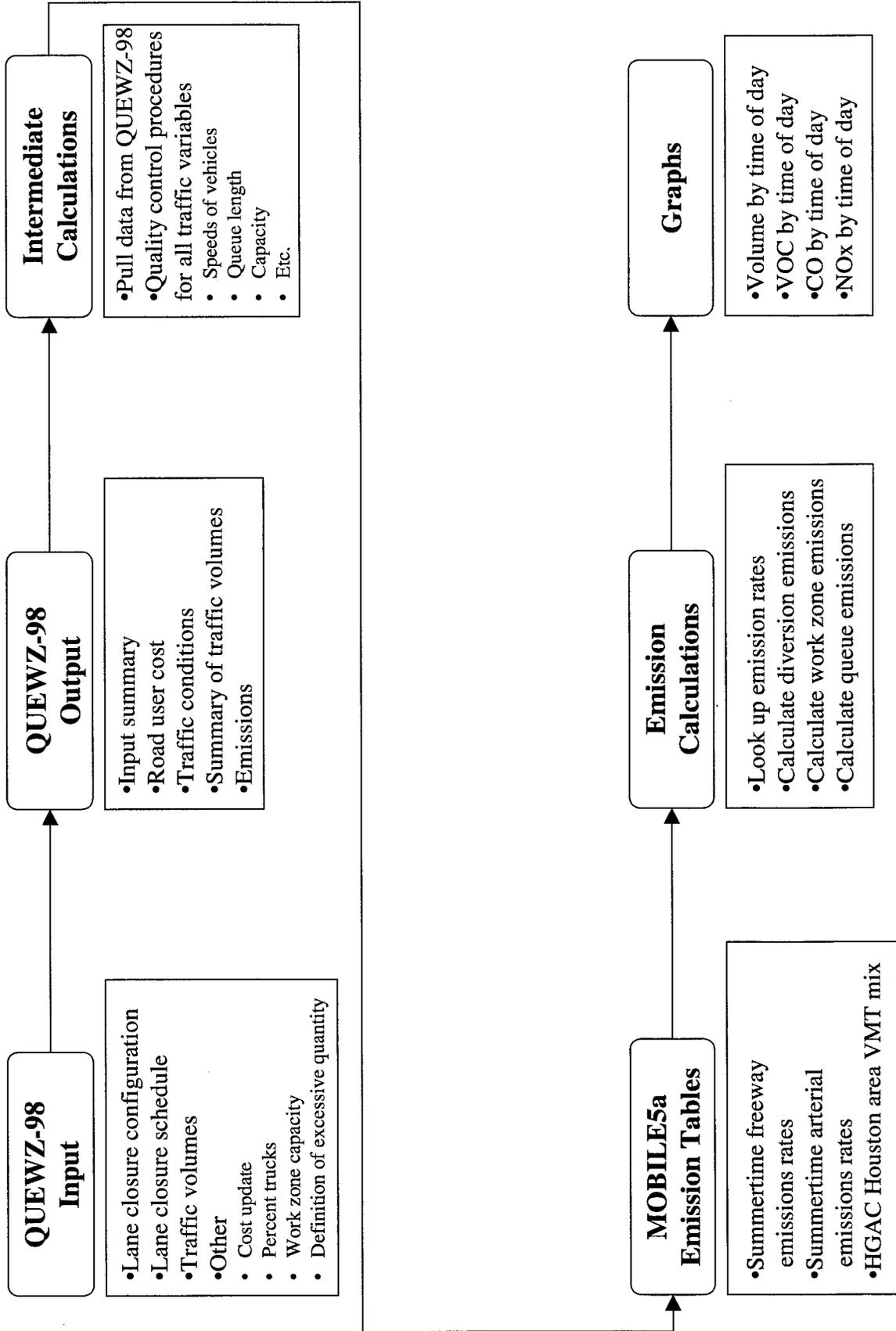


Figure 5. Flow Chart for Work Zone Emissions Calculations.

4. Open the Emissions Workbook, be sure the paste sheet is open, and insert the copied section to cell A1.

Slightly modified procedures were used with the remaining scenarios to pull the QUEWZ-98 output into the paste sheet; however, the calculations performed within the Emissions Workbook are identical. The Dallas peak and Houston peak schedule scenarios modeled construction work zones set up before a peak period, removed during the peak period, then reestablished after the peak period. One limitation of QUEWZ-98 is that only a single work zone closure can be simulated during a 24-hour period. In order to simulate two work zone closures during a 24-hour period, two QUEWZ-98 files needed to be created. Each file contained 12 hours of volumes and one work zone closure, i.e., creating two separate files did not double the 24-hour volume. Combining the two halves of the output files then produced the results for those scenarios.

The overnight scenarios also required a modified procedure. Another limitation of QUEWZ-98 is that volume data are entered for a 24-hour period beginning at 00:00 and ending at 23:00. Simulating an overnight schedule such as 21:00 to 05:00 would either require creating two files, one to contain the 21:00 to 00:00 portion and another to contain the 00:00 to 05:00 portion, or simply shifting the corresponding volumes and times. Shifting the volume data by 20 hours such that 20:00 corresponded with 00:00 created a single file for each overnight scenario in QUEWZ-98. Another limitation of QUEWZ-98 is that it does not echo the hourly volumes in the output of scenarios where no queues form, resulting in a three page output rather than four pages. As this was the case in all overnight scenarios due to low volumes, the hourly volumes were entered manually into the intermediate calculations spreadsheet.

Hourly volumes were manually entered into cells Y5:Y29 of the intermediate calculations sheet for the overnight scenario files. The user can open the QUEWZ-98 output files as above, but before the information is copied, eight rows need to be inserted (start at row 38 and highlight to row 45, right click the mouse and insert the rows). The user can then follow steps three and four as above. This procedure aligns the input file so that the worksheet will look up the proper values.

The next types of data required in the paste sheet are vehicle speeds and queue lengths. These two variables came from the QUEWZ-98 model. If QUEWZ-98 did not generate a speed or a queue, it was assumed that the vehicles were traveling at free-flow speed and that no queue was present (these are conditions where QUEWZ-98 does not echo data in the output file). Once all the variables are determined, the rest of the procedure is fairly straightforward.

Once the QUEWZ-98 output is in the workbook, the program performs the emission calculations. In addition to the tables generated by this workbook, a series of graphs is also generated which serves as a means of quality control to check the output from the QUEWZ-98 model. The following sections document these steps.

QUEWZ-98 Intermediate Calculations

A lot of the problems in calculating the emissions come from the fact that the QUEWZ-98 model does not report all the traffic volumes. If no delay is incurred during a time period, then the traffic volume for that time period is not reported in the output. Much of the logic in the workbook is checking to see if a number is present in the QUEWZ-98 output and, if not, inserting a computed number or default number.

The QUEWZ-98 intermediate calculations sheet serves as a preprocessor to get the correct volume and speed numbers from the QUEWZ-98 output. A lot of the assumptions on the speed and volumes are contained in the next two sheets (QUEWZ-98 intermediate calculations and emission calculations). Some of the information is pulled from the QUEWZ-98 output, the user enters some, and some is calculated.

A series of colors is used to aid in the discussion and to allow the user to determine how the data flow from one sheet to another. Yellow indicates cells for which the user must enter information. The cells highlighted in blue are information pulled from the QUEWZ-98 output. All calculated numbers are represented by green cells.

First, the user must enter information into the yellow cells. The length of the diversion is entered in miles in cell E3 (3 miles). Next, the assumed free-flow speed of the vehicles on the freeway (60 mph) is entered into cell I4. The last item the user must enter is the average speed on the diversion route (20 mph), placed in cells N9:N32.

The information pulled from the QUEWZ-98 output is designated by the blue cells. In some cases the QUEWZ-98 model did not output a fourth page "Summary of Traffic Volumes." In these cases the traffic volumes were regenerated using the same directional and hourly distributions as QUEWZ-98. The AADT from the QUEWZ-98 output (paste sheet D29) is multiplied by columns D and G from the percent AADT and directional distribution sheet. The capacity of the facility is given in the QUEWZ-98 output, but is generated using the default lane capacity based on the number of lanes if omitted in the output.

The QUEWZ-98 model provides all other information with the exception of the time spent in the queue. This variable is calculated using the queue length and queue speed, which in heavy queues was less than the work zone speed. Once the time in the queue is determined, it is assumed that 5 percent of that time is spent at a complete stop. This figure is based on analysis of congested peak hour travel time runs in the Houston area (1998 Houston/Galveston Area Council [HGAC] Travel Time and Speed Survey) (3). This 5 percent stop time is significant because the emission rates for stopped vehicles are substantially higher than those of slow moving vehicles.

Emission Calculations Sheet

Calculating emissions required two different sets of emission look-up tables: a freeway table and an arterial table. The following steps describe the emission calculation procedure. The speed for a facility determines the emission rate that is looked up from the MOBILE5a emissions

table. The traffic volume and length of the affected area are multiplied by this emission rate. This scenario is complicated by different parts of the affected area having different speeds and lengths. The illustration in Figure 6 will aid in the discussion. The approach is assumed to be free-flowing traffic up to the queue zone (if present). The queue zone, as defined by the QUEWZ-98 model, is based on the assumption that vehicles will start to divert if a queue two miles long develops upstream of the work zone. Finally, the work zone is the area where the lane closure and the construction occur. As shown in Figure 6, it is assumed that the diversion route is equal to the length of the combined queue zone and the work zone. This is the same assumption that the QUEWZ-98 model uses for the road user cost estimations.

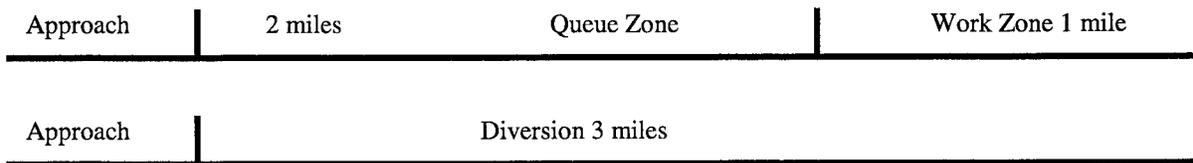


Figure 6. Illustration of Assumed Diversion Route Length.

Assumptions made when calculating the vehicle emissions on the freeway and on the diversion route include:

- The diversion route is equal to the combined length of the work zone and queue zone.
- Vehicles will divert to an alternate route if a queue extends more than two miles.
- Vehicles on the diversion route will average 20 mph (based on Houston area arterial travel time data).
- Work zone speed is 30 mph (queue zone speeds may be considerably lower).
- Queue zone speeds vary based on the QUEWZ-98 model output.
- Traffic is assumed to be traveling at a free-flow speed of 60 mph if the QUEWZ-98 model provides no vehicle speed.
- Vehicles in the queue zone will be stopped 5 percent of the time based on a sample of Houston area freeway segments (1998 HGAC Travel Time and Speed Survey).

MOBILE5a Emissions Table Sheet

This sheet contains the MOBILE5a emission rates for eight different vehicle classifications in the Houston area. These rates are provided for speeds from 3 mph to 65 mph for summertime conditions. The idle emissions (g/hour) were calculated using a per hour emission rate (multiplying the 3 mph rate by three). The pollutants modeled in the Emissions Workbook include:

| | |
|-----|------------------------------------|
| VOC | Volatile Organic Compound (g/mile) |
| CO | Carbon Monoxide (g/mile) |
| NOx | Nitrous Oxide (g/mile) |

The vehicle types included in the emissions tables are:

| | |
|-------|---------------------------|
| LDGV | Light-Duty Gas Vehicle |
| LDGT1 | Light-Duty Gas Truck 1 |
| LDGT2 | Light-Duty Gas Truck 2 |
| HDGV | Heavy-Duty Gas Vehicle |
| LDDV | Light-Duty Diesel Vehicle |
| LDDT | Light-Duty Diesel Truck |
| HDDV | Heavy-Duty Diesel Vehicle |
| MC | Motorcycle |

The two sets of composite emission rate tables were created using HGAC vehicle miles traveled (VMT) mix data for Houston area arterials and freeways. Table 3 presents the arterial and freeway vehicle mixes used in the composite emission rate tables. The definitions for the abbreviated vehicle types in the table are listed above.

Table 3. Percentage of Vehicles used in HGAC Emission Rate Tables.

| | LDGV | LDGT1 | LDGT2 | HDGV | LDDV | LDDT | HDDV | MC |
|---------------------------------|---------|---------|--------|--------|--------|--------|--------|-------|
| HGAC 1997-1999 Arterial VMT Mix | 69.857 | 16.9978 | 5.0277 | 2.1106 | 0.2028 | 0.2111 | 5.4932 | 0.100 |
| HGAC 1997-1999 Freeway VMT Mix | 74.3923 | 13.0695 | 3.9575 | 1.9477 | 0.2159 | 0.1623 | 6.1548 | 0.100 |

USING THE RESULTS

This section provides information on potential uses of task results. Researchers evaluated the impact of construction projects with respect to road user costs, NO_x, CO, and VOC. The range of work zone scenarios in this evaluation simulated various lane closure configurations, traffic demand, and work zone schedules. The number of lanes in the section of roadway varied from two to five lanes. The number of lanes closed due to the work zone varied from one to four lanes. Three levels of traffic demand were simulated using AADT data from Houston freeways and interstates. Finally, the simulations incorporated seven different construction schedules.

The seven schedules can be grouped into three categories: schedules that encompass a peak-direction peak-period (referred to as peak schedules), schedules that do not encompass a peak-direction peak-period (referred to as off-peak schedules), and an overnight schedule. The times associated with these seven construction schedules are presented in Table 1. Three peak schedules evaluated included: base peak schedule (typical schedule without construction bans), a Dallas peak schedule (construction delayed until 10:00), and a Houston peak schedule (construction delayed until 12:00). Three off-peak schedules evaluated included: base off-peak schedule (typical schedule without construction bans), a Dallas off-peak schedule (construction delayed until 10:00), and a Houston off-peak schedule (construction delayed until 12:00).

TABLES AND GRAPHS

The road user cost information was pulled from the original QUEWZ-98 output file (one for each of the 161 scenarios) and the emissions information pulled from the Emissions Workbook file. Consolidating this information into a large matrix table allowed researchers to create a series of graphs for each geometric/volume scenario with a series of curves representing the different road closure scenarios. These graphs provide the user a means of comparing the impact of different road closure scenarios. The impact of schedule and number of lanes closed are presented in road user cost, NO_x, CO, and VOC graphs for the following scenarios:

three-lane section:

- low volume, and
- medium volume.

four-lane section:

- low volume, and
- medium volume.

five-lane section:

- low volume,
- medium volume, and
- high volume.

To illustrate the use of these graphs, refer to Figures 7-10. Figure 7 details the road user costs associated with the seven different construction schedules and the number of lanes closed in the work zone for a medium volume, four-lane section. In order to combine the data from various scenarios (one of four lanes closed, two of four lanes closed, and three of four lanes closed), volume per lane is used as the common x-axis. The AADT used in all medium volume scenarios was 110,000 vehicles per day, which corresponds to 55,000 vehicles per day per direction, assuming a 50/50 directional split.

The three data points on each trend line in Figure 7, moving from left to right, indicate the associated road user cost for one of four lanes closed (corresponds to approximately 18,500 vehicles per day per lane [vpdpl]), two of four lanes closed (corresponds to approximately 27,500 vpdpl) and three of four lanes closed (corresponds to approximately 55,000 vpdpl). Thus, the road user cost associated with closing one lane (first data point on trend line) on a medium volume, four-lane section using the base off-peak schedule (top trend line) would be approximately \$31,000 per day. Similarly, the road user cost associated with closing two lanes (second data point on trend line) on a medium volume, four-lane section using the Off-Peak Base Schedule would be approximately \$69,000 per day. Similarly, Figures 8, 9, and 10 show the impacts of schedule and number of lanes closed for CO, VOC, and NO_x respectively.

The Appendix contains the complete series of tables and graphs to document the results of this task. No graphs are included for the scenarios involving a one-lane closure of a two-lane section as they would only involve a single data point for each schedule. The results of these

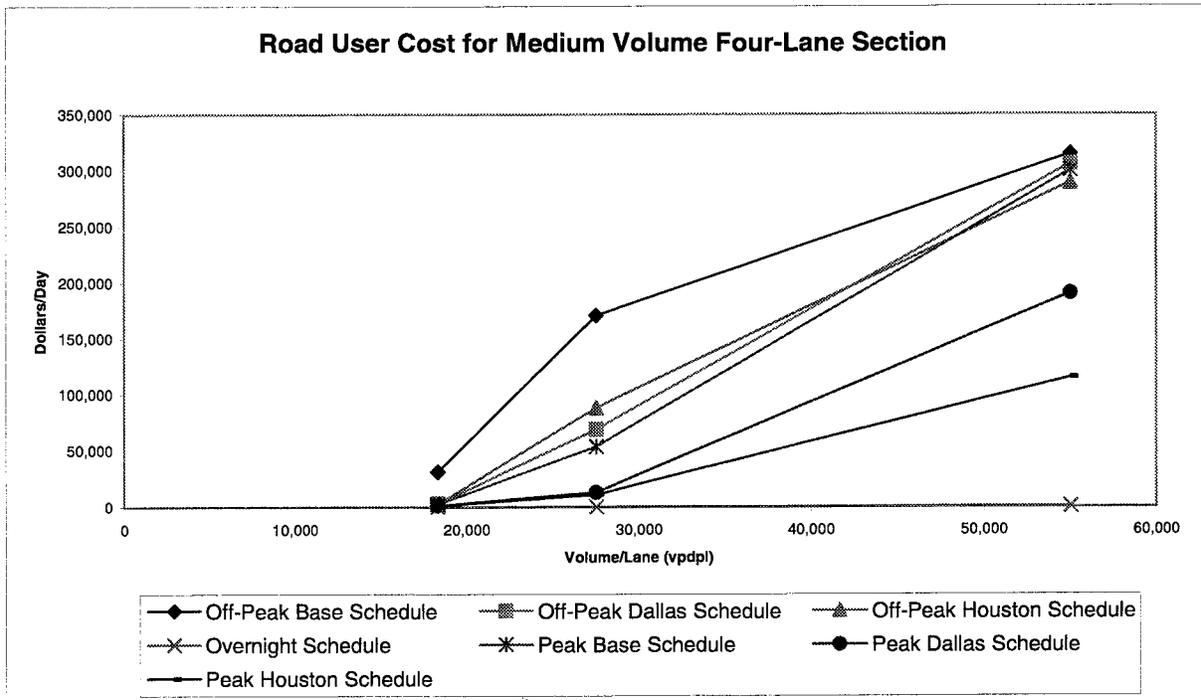


Figure 7. Example of Road User Cost for Medium Volume Four-Lane Section.

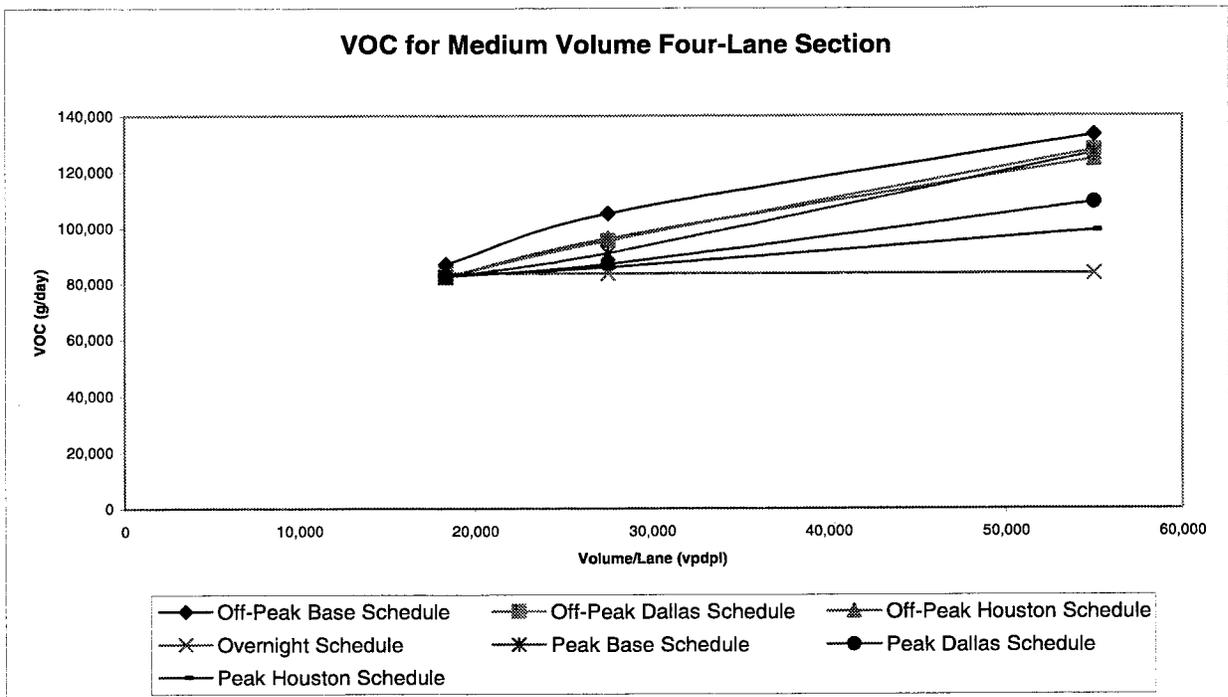


Figure 8. Example of VOC for Medium Volume Four-Lane Section.

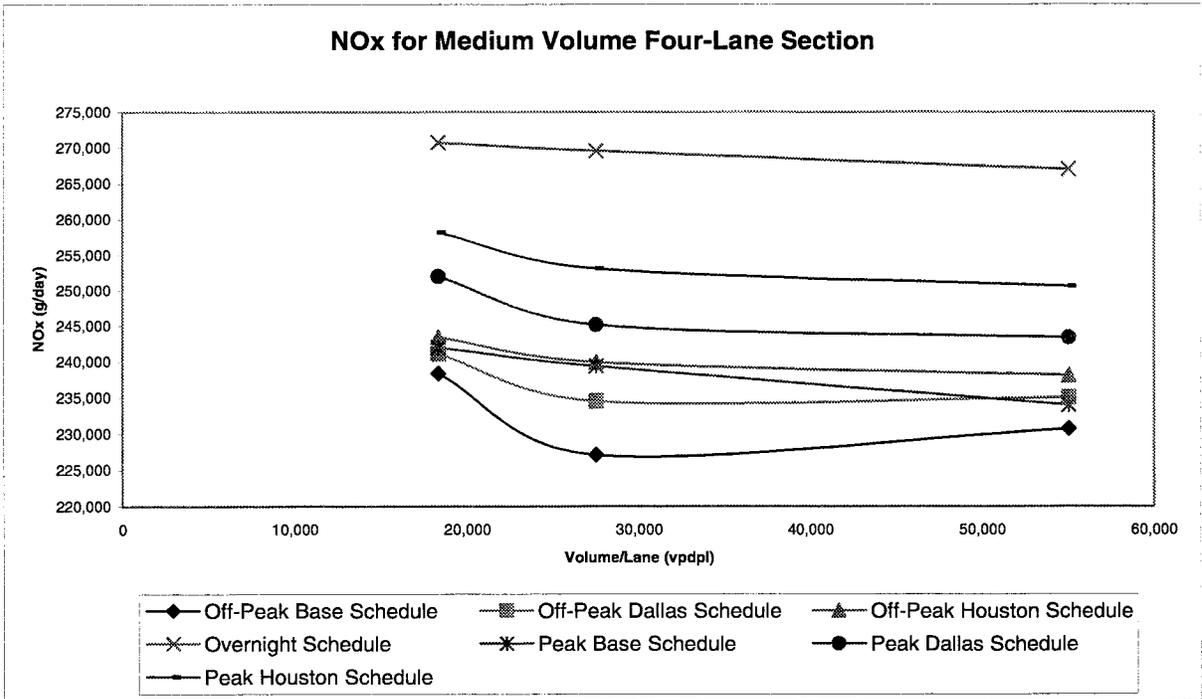


Figure 9. Example of NOx for Medium Volume Four-Lane Section.

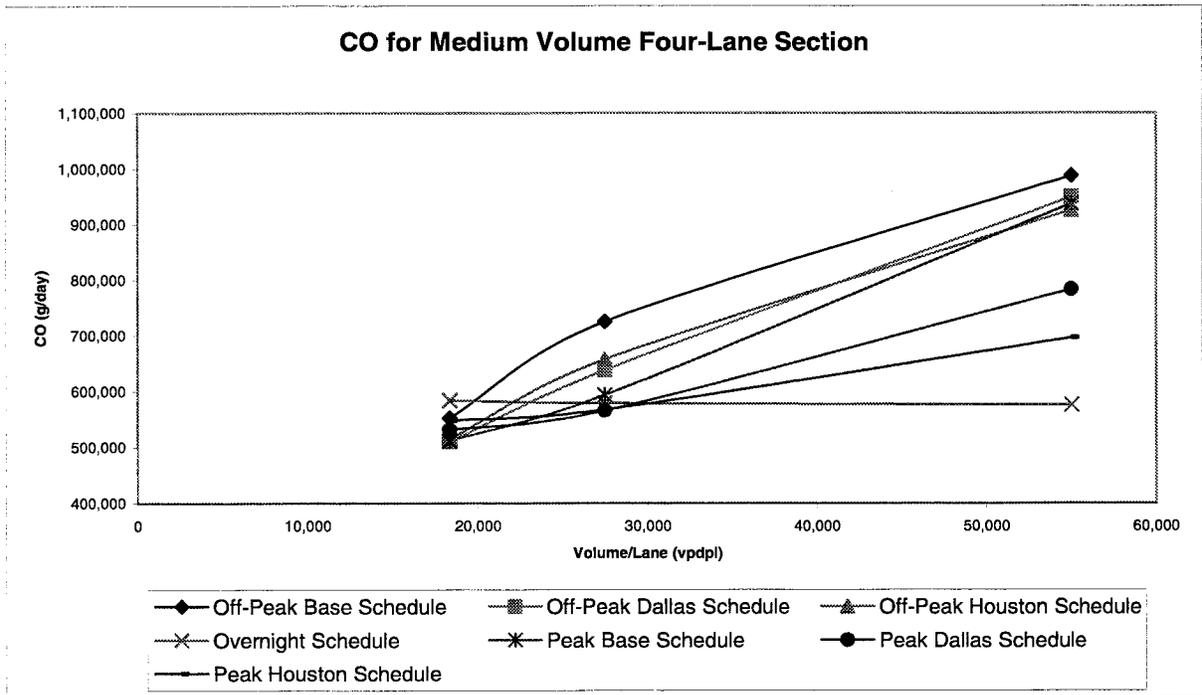


Figure 10. Example of CO for Medium Volume Four-Lane Section.

scenarios are presented in Table A-1. The following sample problems are provided to show potential uses of the results of this task.

SAMPLE PROBLEM 1 – IMPACT OF INCREASED PROJECT DURATION DUE TO SCHEDULE SHIFT

The information derived in this project can be used to show the impacts of construction shifts with respect to road user costs and emissions. Changes in these values occur as a result from an increase or decrease of daily values as well as a lengthening of project duration due to the schedule shift. Task 5 of this project evaluated the effect of various construction schedules with respect to project duration (4). The results of this task that gathered data from contractors in the Houston/Galveston area are shown in Table 4.

Table 4. Average Impacts in Project Duration Estimated by Houston Contractors.

| Work Schedule Alternative | Sample Hours | Contractor Estimated Increase |
|---|----------------------------------|-------------------------------|
| Delayed, Continuous Operation | 12:00 to 20:00 | 5% |
| Partially Delayed, Continuous Operation | 10:00 to 18:00 | 10% |
| Delayed, Non-Continuous Operation | 12:00 to 15:00 19:00 to 24:00 | 19% |
| Continuous Nighttime Operation | 21:00 to 05:00 | 12% |

To demonstrate the impact of work schedule shifts with respect to road user costs and emissions, the following sample project can be considered. Suppose a project is normally scheduled to have a duration of three months. The project requires one lane in a three-lane section to be closed for a one-mile work zone. The facility serves a medium level AADT. The impacts of the alternative schedules are presented with respect to road user costs and NOx in Tables 5 and 6, respectively. These tables use contractor estimates of project duration increases and results of simulations from QUEWZ-98 and the Emissions Workbook. These increases (last column) are solely due to project lengthening associated with each schedule and do not include other costs that may be incurred with some of the schedules. For example, overnight schedules may incur higher equipment costs to provide lighting and higher labor costs. Similarly the non-continuous schedule requires more worker time to be spent setting up and taking down the work zone, i.e., workers set up the work zone, remove it for the peak period, then reestablish it.

The results of this example show that the road user costs decrease as the construction schedule is moved out of the peak period. However, this also increases vehicle speeds, which in turn increase the NOx emissions generated by the respective work zone schedules.

Table 5. Estimated Impact of Increased Project Duration on Road User Cost.

| Construction Schedule | Percent Increase | Duration of Project | Days Increased | Daily Road User Cost | Total Road User Cost | Differential Cost |
|-----------------------|------------------|---------------------|----------------|----------------------|----------------------|-------------------|
| Base | 0 | 60 | 0 | \$ 132,225 | \$ 7,933,500 | - |
| Delayed Continuous | 5% | 60 | 3 | \$ 73,345 | \$ 4,620,735 | \$ (3,312,765) |
| Partial Delay | 10% | 60 | 6 | \$ 61,533 | \$ 4,061,178 | \$ (3,872,322) |
| Non-Continuous | 19% | 60 | 11.4 | \$ 11,268 | \$ 804,535 | \$ (7,128,965) |
| Nighttime | 12% | 60 | 7.2 | \$ 161 | \$ 10,819 | \$ (7,922,681) |

Table 6. Estimated Impact of Increased Project Duration on NOx Emissions.

| Construction Schedule | Percent Increase | Duration of Project | Days Increased | Daily NOx (kg) | Total NOx (kg) | Differential NOx (kg) |
|-----------------------|------------------|---------------------|----------------|----------------|----------------|-----------------------|
| Base | 0 | 60 | 0 | 226 | 13,574 | - |
| Delayed Continuous | 5% | 60 | 3 | 238 | 15,018 | 1,444 |
| Partial Delay | 10% | 60 | 6 | 227 | 14,987 | 1,413 |
| Non-Continuous | 19% | 60 | 11.4 | 231 | 16,472 | 2,898 |
| Nighttime | 12% | 60 | 7.2 | 244 | 16,375 | 2,801 |

SAMPLE PROBLEM 2 - IMPACT OF SCHEDULE OR NUMBER OF LANES CLOSED IN WORK ZONE

One application of the results of this project may be to make comparisons of the relative impact of schedule alternatives or number of lanes closed in the work zone with respect to road user cost and emissions. For this example, consider a project in Dallas involving a medium volume, four-lane section roadway. Suppose the construction work will require two lanes of the four-lane section to be closed for the work zone. Figure 7 can be utilized to determine the approximate road user costs associated with each of the construction schedules. Figures 8 through 10 can be utilized to determine the impact on emissions. The results of the comparison between several schedules (base, Dallas [construction delayed until 10:00], and overnight) are summarized in Table 7. With respect to road user cost, the overnight schedule incurs the lowest cost due to the low volumes associated with nighttime and early morning conditions, while the Dallas and base schedules incur higher costs, as more vehicles are impacted by the work zone.

Table 7. Impact of Schedule on Daily Road User Cost and Emissions.

| Measure | Schedule | | |
|-------------------------|-----------------|-------------------|-----------|
| | Base (Off-Peak) | Dallas (Off-Peak) | Overnight |
| Road User Cost (\$/day) | 170,805 | 69,189 | 175 |
| CO (g/day) | 725,485 | 638,235 | 579,216 |
| VOC (g/day) | 105,231 | 95,410 | 83,565 |
| NOx (g/day) | 227,074 | 234,519 | 269,565 |

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3. Benz, R., Hamilton, C., and Byrd, S. Houston-Galveston Regional Transportation Study: 1998 Travel Time and Speed Survey. Texas Transportation Institute, College Station, Texas, June 1999.
4. Trejo, D., Anderson, S., Kuennen, S., De Las Casas, R., and Deshmukh, R. Potential Cost and Schedule Impacts from the TNRCC Proposed Rule Restricting the Use of Construction Equipment. Preliminary Findings. Texas Transportation Institute, College Station, Texas, December 2000.

Appendix

Task 6: Contribution of Vehicular Emissions Caused by Reduction in Capacity during Roadway Construction

Emissions Tables and Graphs Road User Cost Tables and Graphs

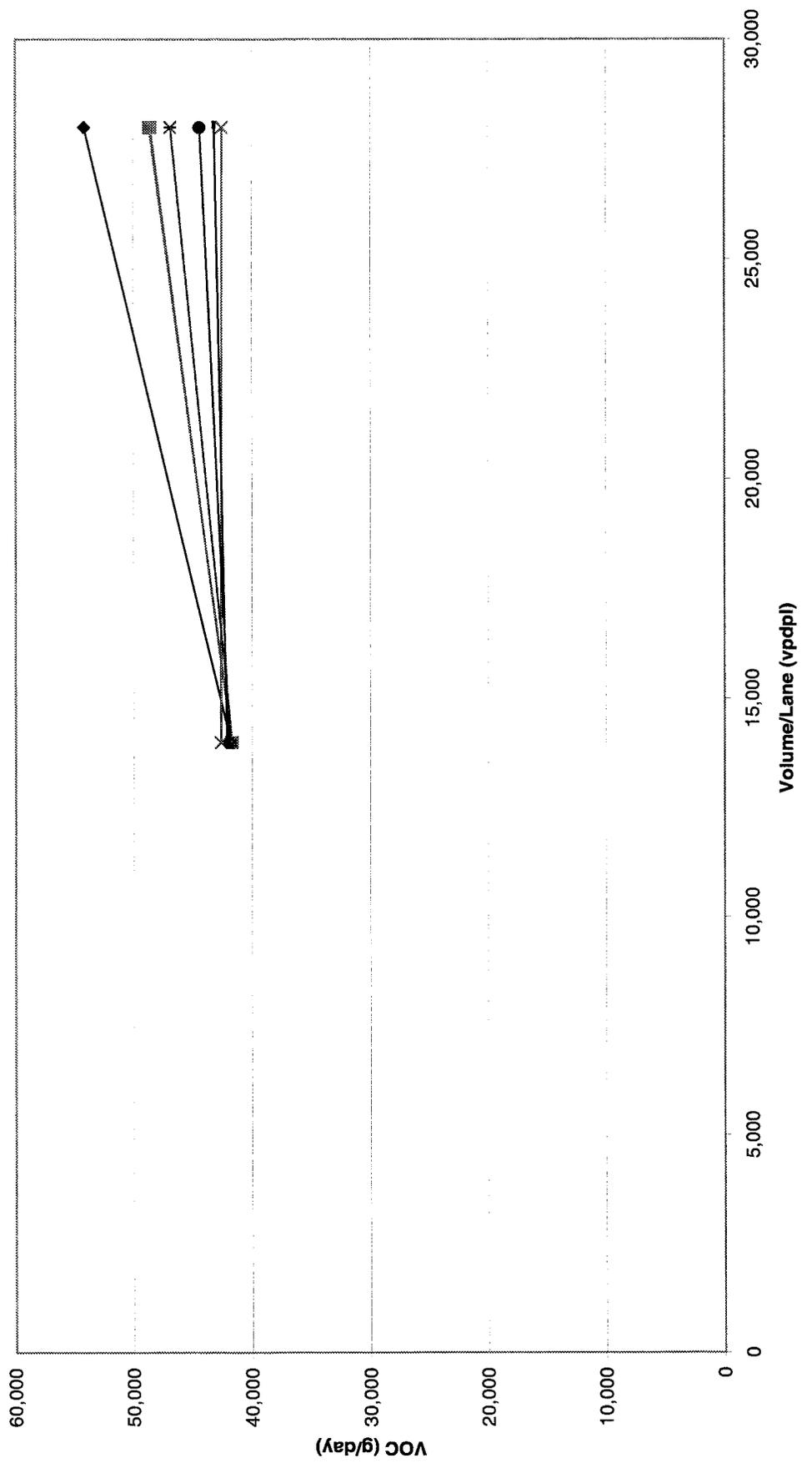
Table A-1. All Scenarios Emissions & Road User Costs (1 of 2)

| | Number of lanes | | ADT per Lane | Off-Peak Base Schedule | | | | | | Off-Peak Dallas Schedule | | | | | | Off-Peak Houston Schedule | | | | | | Overnight Schedule | | | | | | | | | | | | | | |
|---------------------|-------------------|------|--------------|------------------------|-----------|-----------|---------|---------|-----------|--------------------------|---------|---------|-----------|-----------|---------|---------------------------|-----------|---------------------|---------|---------|-----------|--------------------|---------|---------|-----------|---------------------|---------|---------|-----------|-----------|---------|---------|---------|---------|---------|-----|
| | Total | Open | | VOC | | CO | | NOx | | Road User Cost (\$) | | VOC | | CO | | NOx | | Road User Cost (\$) | | VOC | | CO | | NOx | | Road User Cost (\$) | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Low AADT 56,000 | 2 | 1 | 28000 | 54,401 | 377,745 | 115,319 | 86,994 | 49,567 | 335,929 | 119,550 | 49,059 | 49,266 | 338,092 | 122,533 | 49,266 | 338,092 | 122,533 | 49,266 | 338,092 | 122,533 | 49,266 | 338,092 | 122,533 | 49,266 | 338,092 | 122,533 | 49,266 | 338,092 | 122,533 | 51,282 | 42,543 | 294,876 | 137,234 | 91 | | |
| | 3 | 2 | 14000 | 41,790 | 258,091 | 124,052 | 1,256 | 41,684 | 260,254 | 126,084 | 851 | 41,723 | 262,384 | 127,004 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 67,486 | 42,643 | 298,217 | 138,000 | 44 | | |
| | 3 | 1 | 28000 | 54,137 | 375,615 | 116,201 | 127,242 | 48,638 | 328,308 | 121,212 | 50,048 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 67,486 | 42,643 | 294,876 | 137,234 | 98 | | |
| | 4 | 3 | 9333 | 41,420 | 257,728 | 128,549 | 576 | 41,462 | 260,996 | 130,193 | 428 | 41,723 | 262,384 | 127,004 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 395 | 42,690 | 299,629 | 136,276 | 35 | | |
| | 4 | 2 | 14000 | 41,790 | 258,091 | 124,052 | 1,349 | 41,684 | 260,254 | 126,084 | 924 | 41,723 | 262,384 | 127,004 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 48,546 | 331,637 | 123,559 | 848 | 42,643 | 298,217 | 138,000 | 47 | | |
| | 4 | 1 | 28000 | 53,771 | 372,776 | 116,596 | 164,425 | 47,848 | 322,068 | 122,337 | 51,580 | 48,450 | 331,149 | 123,385 | 48,450 | 331,149 | 123,385 | 48,450 | 331,149 | 123,385 | 48,450 | 331,149 | 123,385 | 48,450 | 331,149 | 123,385 | 48,450 | 331,149 | 77,896 | 42,543 | 294,876 | 137,234 | 102 | | | |
| | 5 | 4 | 7000 | 41,548 | 263,706 | 130,660 | 372 | 41,622 | 267,019 | 131,895 | 291 | 41,723 | 270,127 | 132,496 | 270 | 41,723 | 270,127 | 132,496 | 270 | 41,723 | 270,127 | 132,496 | 270 | 41,723 | 270,127 | 132,496 | 270 | 41,723 | 270,127 | 270 | 42,720 | 300,542 | 138,459 | 31 | | |
| | 5 | 3 | 9333 | 41,420 | 257,728 | 128,549 | 625 | 41,462 | 260,998 | 130,193 | 466 | 41,568 | 264,269 | 130,821 | 430 | 41,568 | 264,269 | 130,821 | 430 | 41,568 | 264,269 | 130,821 | 430 | 41,568 | 264,269 | 130,821 | 430 | 41,568 | 264,269 | 130,821 | 430 | 42,690 | 299,629 | 138,276 | 36 | |
| | 5 | 2 | 14000 | 41,790 | 258,091 | 124,052 | 1,401 | 41,684 | 260,254 | 126,084 | 965 | 41,723 | 262,384 | 127,004 | 886 | 41,723 | 262,384 | 127,004 | 886 | 41,723 | 262,384 | 127,004 | 886 | 41,723 | 262,384 | 127,004 | 886 | 41,723 | 262,384 | 127,004 | 886 | 42,643 | 298,217 | 138,000 | 49 | |
| | 5 | 1 | 28000 | 53,551 | 371,030 | 116,889 | 199,646 | 47,311 | 318,849 | 123,478 | 51,123 | 47,823 | 326,670 | 124,433 | 80,520 | 47,823 | 326,670 | 124,433 | 80,520 | 47,823 | 326,670 | 124,433 | 80,520 | 47,823 | 326,670 | 124,433 | 80,520 | 47,823 | 326,670 | 124,433 | 80,520 | 42,543 | 294,876 | 137,234 | 104 | |
| Medium AADT 110,000 | 3 | 2 | 27500 | 105,803 | 730,540 | 226,238 | 132,225 | 96,540 | 648,606 | 232,387 | 61,533 | 97,065 | 665,065 | 238,377 | 97,065 | 665,065 | 238,377 | 97,065 | 665,065 | 238,377 | 97,065 | 665,065 | 238,377 | 97,065 | 665,065 | 238,377 | 97,065 | 665,065 | 238,377 | 73,345 | 83,565 | 579,215 | 269,565 | 161 | | |
| | 3 | 1 | 55000 | 133,170 | 988,674 | 229,956 | 238,584 | 128,052 | 951,997 | 234,293 | 231,660 | 124,748 | 927,956 | 237,708 | 219,256 | 124,748 | 927,956 | 237,708 | 219,256 | 124,748 | 927,956 | 237,708 | 219,256 | 124,748 | 927,956 | 237,708 | 219,256 | 124,748 | 927,956 | 237,708 | 219,256 | 83,632 | 576,499 | 266,972 | 560 | |
| | 4 | 3 | 18333 | 86,910 | 552,517 | 238,378 | 31,210 | 82,343 | 510,510 | 241,092 | 2,709 | 82,377 | 514,722 | 243,424 | 2,479 | 82,377 | 514,722 | 243,424 | 2,479 | 82,377 | 514,722 | 243,424 | 2,479 | 82,377 | 514,722 | 243,424 | 2,479 | 82,377 | 514,722 | 243,424 | 2,479 | 83,704 | 583,962 | 270,720 | 101 | |
| | 4 | 2 | 27500 | 105,231 | 725,485 | 227,075 | 170,805 | 95,410 | 638,235 | 234,519 | 69,189 | 96,241 | 657,624 | 239,933 | 88,520 | 96,241 | 657,624 | 239,933 | 88,520 | 96,241 | 657,624 | 239,933 | 88,520 | 96,241 | 657,624 | 239,933 | 88,520 | 96,241 | 657,624 | 239,933 | 88,520 | 83,565 | 579,215 | 269,565 | 175 | |
| | 5 | 4 | 13750 | 82,087 | 508,964 | 243,673 | 2,221 | 81,879 | 511,213 | 247,666 | 1,501 | 81,956 | 515,398 | 249,472 | 1,378 | 81,956 | 515,398 | 249,472 | 1,378 | 81,956 | 515,398 | 249,472 | 1,378 | 81,956 | 515,398 | 249,472 | 1,378 | 81,956 | 515,398 | 249,472 | 1,378 | 83,763 | 585,779 | 271,068 | 80 | |
| | 5 | 3 | 18333 | 86,278 | 547,077 | 239,702 | 31,258 | 82,343 | 510,510 | 241,092 | 2,909 | 82,377 | 514,722 | 243,424 | 2,661 | 82,377 | 514,722 | 243,424 | 2,661 | 82,377 | 514,722 | 243,424 | 2,661 | 82,377 | 514,722 | 243,424 | 2,661 | 82,377 | 514,722 | 243,424 | 2,661 | 83,704 | 583,962 | 270,720 | 109 | |
| | 5 | 2 | 27500 | 105,205 | 725,604 | 228,036 | 208,658 | 94,584 | 630,509 | 235,884 | 76,289 | 95,761 | 653,217 | 240,944 | 104,178 | 95,761 | 653,217 | 240,944 | 104,178 | 95,761 | 653,217 | 240,944 | 104,178 | 95,761 | 653,217 | 240,944 | 104,178 | 95,761 | 653,217 | 240,944 | 104,178 | 83,565 | 579,215 | 269,565 | 193 | |
| | 5 | 1 | 55000 | 133,378 | 989,278 | 231,749 | 389,252 | 127,532 | 948,145 | 235,556 | 378,566 | 124,240 | 923,430 | 238,428 | 358,030 | 124,240 | 923,430 | 238,428 | 358,030 | 124,240 | 923,430 | 238,428 | 358,030 | 124,240 | 923,430 | 238,428 | 358,030 | 124,240 | 923,430 | 238,428 | 358,030 | 83,632 | 576,499 | 266,972 | 585 | |
| | High AADT 180,000 | 5 | 4 | 22500 | 151,193 | 992,044 | 383,098 | 74,405 | 140,225 | 885,954 | 386,799 | 10,251 | 140,212 | 882,832 | 391,284 | 9,650 | 140,212 | 882,832 | 391,284 | 9,650 | 140,212 | 882,832 | 391,284 | 9,650 | 140,212 | 882,832 | 391,284 | 9,650 | 140,212 | 882,832 | 391,284 | 9,650 | 136,822 | 950,954 | 442,125 | 195 |
| | | 5 | 3 | 30000 | 182,067 | 1,291,207 | 369,939 | 241,825 | 171,272 | 1,199,942 | 380,394 | 197,106 | 168,814 | 1,190,041 | 388,322 | 187,531 | 168,814 | 1,190,041 | 388,322 | 187,531 | 168,814 | 1,190,041 | 388,322 | 187,531 | 168,814 | 1,190,041 | 388,322 | 187,531 | 168,814 | 1,190,041 | 388,322 | 187,531 | 136,755 | 947,437 | 440,639 | 305 |
| 5 | | 2 | 45000 | 209,146 | 1,544,916 | 374,745 | 332,584 | 201,322 | 1,483,727 | 381,815 | 322,923 | 195,505 | 1,438,127 | 387,489 | 306,038 | 195,505 | 1,438,127 | 387,489 | 306,038 | 195,505 | 1,438,127 | 387,489 | 306,038 | 195,505 | 1,438,127 | 387,489 | 306,038 | 195,505 | 1,438,127 | 387,489 | 306,038 | 136,787 | 944,731 | 438,293 | 620 | |
| 5 | | 1 | 90000 | 263,172 | 1,894,314 | 387,160 | 632,372 | 228,850 | 1,679,496 | 384,560 | 614,674 | 222,290 | 1,637,142 | 390,358 | 580,866 | 222,290 | 1,637,142 | 390,358 | 580,866 | 222,290 | 1,637,142 | 390,358 | 580,866 | 222,290 | 1,637,142 | 390,358 | 580,866 | 222,290 | 1,637,142 | 390,358 | 139,007 | 952,677 | 430,509 | 36,703 | | |

Table A-1. All Scenarios Emissions & Road User Costs (Continued 2 of 2)

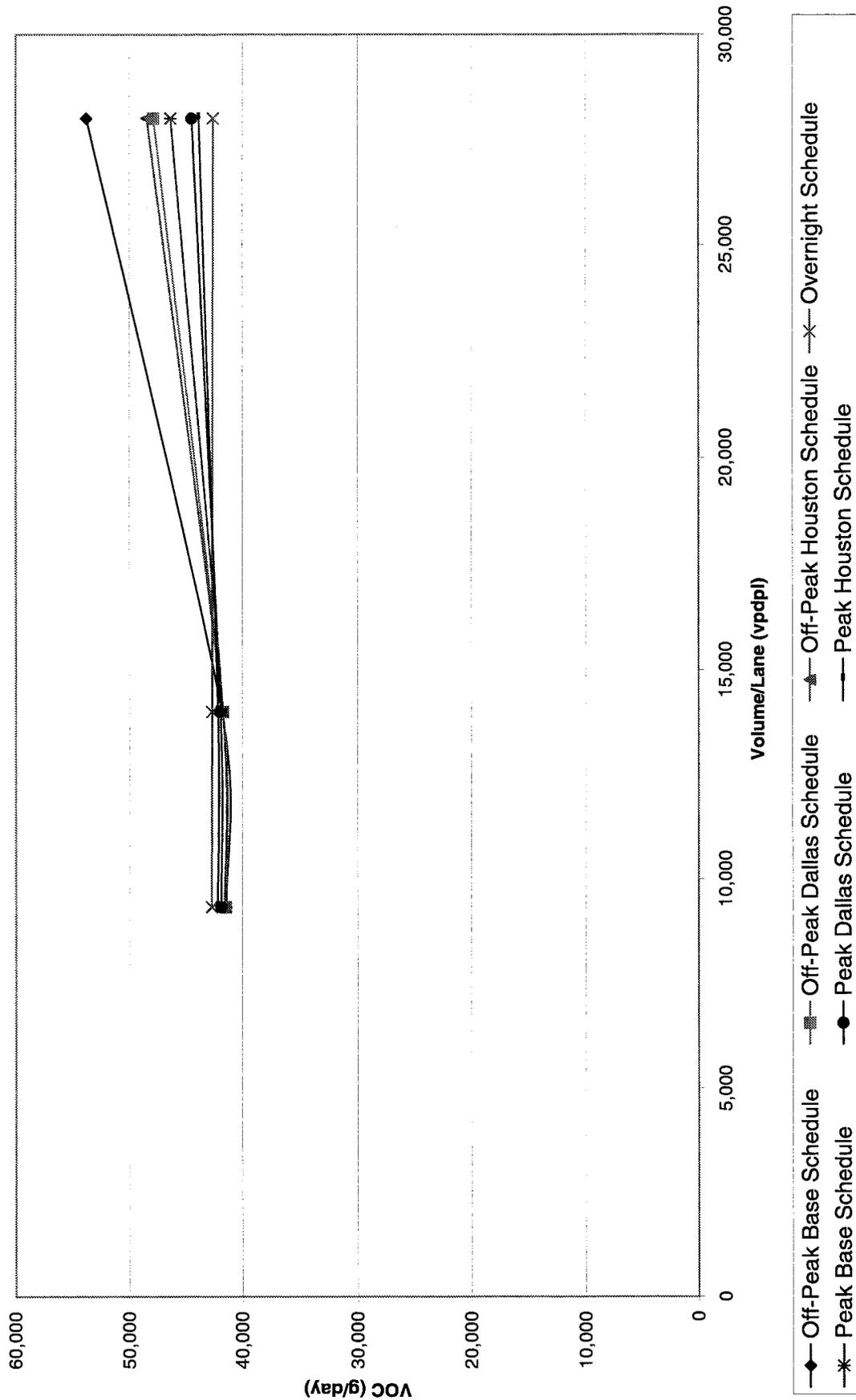
| | Number of lanes | | ADT per Lane | | Peak Base Schedule | | | | | | Peak Dallas Schedule | | | | | | Peak Houston Schedule | | | | | | | |
|------------------------|-----------------|---|--------------|---------|--------------------|---------|---------|---------|-----------|---------|----------------------|---------|-----------|---------|---------|---------|-----------------------|---------|---------|---------|-----------|---------|---------|----|
| | | | | | Open | | NOx | | CO | | VOC | | NOx | | CO | | VOC | | NOx | | CO | | VOC | |
| | | | | | Total | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| Low AADT 56,000 | 2 | 1 | 28000 | 48,080 | 320,072 | 120,731 | 42,483 | 44,543 | 291,234 | 125,135 | 10,657 | 43,284 | 284,899 | 129,346 | 8,079 | 43,284 | 284,899 | 129,346 | 8,079 | 43,284 | 284,899 | 129,346 | 8,079 | |
| | 3 | 2 | 14000 | 41,691 | 260,981 | 126,478 | 810 | 41,913 | 271,626 | 130,552 | 496 | 42,132 | 279,796 | 132,931 | 346 | 42,132 | 279,796 | 132,931 | 346 | 42,132 | 279,796 | 132,931 | 346 | |
| | 3 | 1 | 28000 | 46,845 | 311,009 | 123,965 | 43,873 | 44,407 | 292,142 | 126,527 | 10,484 | 43,190 | 286,203 | 130,693 | 7,921 | 43,190 | 286,203 | 130,693 | 7,921 | 43,190 | 286,203 | 130,693 | 7,921 | |
| | 4 | 3 | 9333 | 41,475 | 261,730 | 130,530 | 410 | 41,873 | 274,631 | 133,410 | 265 | 42,153 | 283,203 | 135,072 | 189 | 42,153 | 283,203 | 135,072 | 189 | 42,153 | 283,203 | 135,072 | 189 | |
| | 4 | 2 | 14000 | 41,691 | 260,981 | 126,478 | 880 | 41,913 | 271,626 | 130,552 | 540 | 42,132 | 279,796 | 132,931 | 376 | 42,132 | 279,796 | 132,931 | 376 | 42,132 | 279,796 | 132,931 | 376 | |
| | 4 | 1 | 28000 | 46,324 | 309,462 | 125,081 | 43,769 | 44,453 | 294,680 | 127,214 | 10,407 | 43,811 | 293,353 | 130,266 | 7,852 | 43,811 | 293,353 | 130,266 | 7,852 | 43,811 | 293,353 | 130,266 | 7,852 | |
| | 5 | 4 | 7000 | 41,676 | 268,698 | 132,212 | 280 | 42,026 | 279,437 | 134,302 | 188 | 42,257 | 286,472 | 135,683 | 137 | 42,257 | 286,472 | 135,683 | 137 | 42,257 | 286,472 | 135,683 | 137 | |
| | 5 | 3 | 9333 | 41,475 | 261,730 | 130,530 | 447 | 41,873 | 274,631 | 133,410 | 288 | 42,153 | 283,203 | 135,072 | 205 | 42,153 | 283,203 | 135,072 | 205 | 42,153 | 283,203 | 135,072 | 205 | |
| | 5 | 2 | 14000 | 41,691 | 260,981 | 126,478 | 919 | 41,913 | 271,626 | 130,552 | 565 | 42,132 | 279,796 | 132,931 | 393 | 42,132 | 279,796 | 132,931 | 393 | 42,132 | 279,796 | 132,931 | 393 | |
| | 5 | 1 | 28000 | 46,013 | 309,678 | 126,508 | 43,251 | 44,487 | 296,612 | 127,711 | 10,360 | 43,825 | 294,693 | 130,651 | 7,812 | 43,825 | 294,693 | 130,651 | 7,812 | 43,825 | 294,693 | 130,651 | 7,812 | |
| Medium AADT 110,000 | 3 | 2 | 27500 | 92,486 | 607,643 | 235,878 | 52,074 | 87,211 | 567,146 | 243,347 | 13,162 | 86,120 | 569,073 | 251,245 | 11,268 | 86,120 | 569,073 | 251,245 | 11,268 | 86,120 | 569,073 | 251,245 | 11,268 | |
| | 3 | 1 | 55000 | 127,176 | 942,014 | 233,275 | 227,934 | 109,794 | 787,456 | 242,109 | 150,381 | 99,648 | 700,739 | 249,275 | 93,729 | 99,648 | 700,739 | 249,275 | 93,729 | 99,648 | 700,739 | 249,275 | 93,729 | |
| | 4 | 3 | 18333 | 82,342 | 511,920 | 241,970 | 2,561 | 82,546 | 531,341 | 251,963 | 1,509 | 82,877 | 547,590 | 258,158 | 1,038 | 82,877 | 547,590 | 258,158 | 1,038 | 82,877 | 547,590 | 258,158 | 1,038 | |
| | 4 | 2 | 27500 | 90,951 | 594,082 | 239,375 | 53,613 | 86,950 | 565,896 | 245,147 | 13,041 | 85,659 | 567,822 | 253,045 | 11,092 | 85,659 | 567,822 | 253,045 | 11,092 | 85,659 | 567,822 | 253,045 | 11,092 | |
| | 4 | 1 | 55000 | 126,695 | 937,548 | 233,978 | 299,892 | 109,186 | 783,294 | 243,377 | 190,417 | 99,023 | 696,298 | 250,578 | 115,068 | 99,023 | 696,298 | 250,578 | 115,068 | 99,023 | 696,298 | 250,578 | 115,068 | |
| | 5 | 4 | 13750 | 81,893 | 512,641 | 248,438 | 1,428 | 82,329 | 533,551 | 256,441 | 876 | 82,759 | 549,599 | 261,114 | 611 | 82,759 | 549,599 | 261,114 | 611 | 82,759 | 549,599 | 261,114 | 611 | |
| | 5 | 3 | 18333 | 82,342 | 511,920 | 241,970 | 2,752 | 82,546 | 531,341 | 251,963 | 1,628 | 82,877 | 547,590 | 258,158 | 1,119 | 82,877 | 547,590 | 258,158 | 1,119 | 82,877 | 547,590 | 258,158 | 1,119 | |
| | 5 | 2 | 27500 | 92,295 | 608,059 | 238,820 | 54,946 | 86,892 | 566,130 | 246,315 | 12,992 | 85,800 | 568,056 | 254,214 | 11,015 | 85,800 | 568,056 | 254,214 | 11,015 | 85,800 | 568,056 | 254,214 | 11,015 | |
| | 5 | 1 | 55000 | 126,381 | 935,002 | 234,873 | 370,916 | 108,797 | 781,326 | 244,742 | 229,733 | 98,612 | 693,697 | 251,835 | 135,796 | 98,612 | 693,697 | 251,835 | 135,796 | 98,612 | 693,697 | 251,835 | 135,796 | |
| | 5 | 4 | 22500 | 136,947 | 861,233 | 382,370 | 9,467 | 135,628 | 869,726 | 406,853 | 3,705 | 135,960 | 894,641 | 418,537 | 2,525 | 135,960 | 894,641 | 418,537 | 2,525 | 135,960 | 894,641 | 418,537 | 2,525 | |
| High AADT 180,000 | 5 | 3 | 30000 | 170,481 | 1,187,601 | 377,414 | 209,053 | 150,007 | 1,003,270 | 397,087 | 98,843 | 143,885 | 959,576 | 408,713 | 54,871 | 143,885 | 959,576 | 408,713 | 54,871 | 143,885 | 959,576 | 408,713 | 54,871 | |
| | 5 | 2 | 45000 | 199,756 | 1,466,321 | 380,063 | 318,130 | 172,043 | 1,220,141 | 396,762 | 189,206 | 157,421 | 1,092,410 | 407,985 | 109,861 | 157,421 | 1,092,410 | 407,985 | 109,861 | 157,421 | 1,092,410 | 407,985 | 109,861 | |
| | 5 | 1 | 90000 | 226,341 | 1,660,089 | 382,916 | 603,032 | 196,903 | 1,427,453 | 394,704 | 434,035 | 178,125 | 1,277,649 | 404,463 | 329,137 | 178,125 | 1,277,649 | 404,463 | 329,137 | 178,125 | 1,277,649 | 404,463 | 329,137 | |

VOC for Low Volume Three-Lane Section

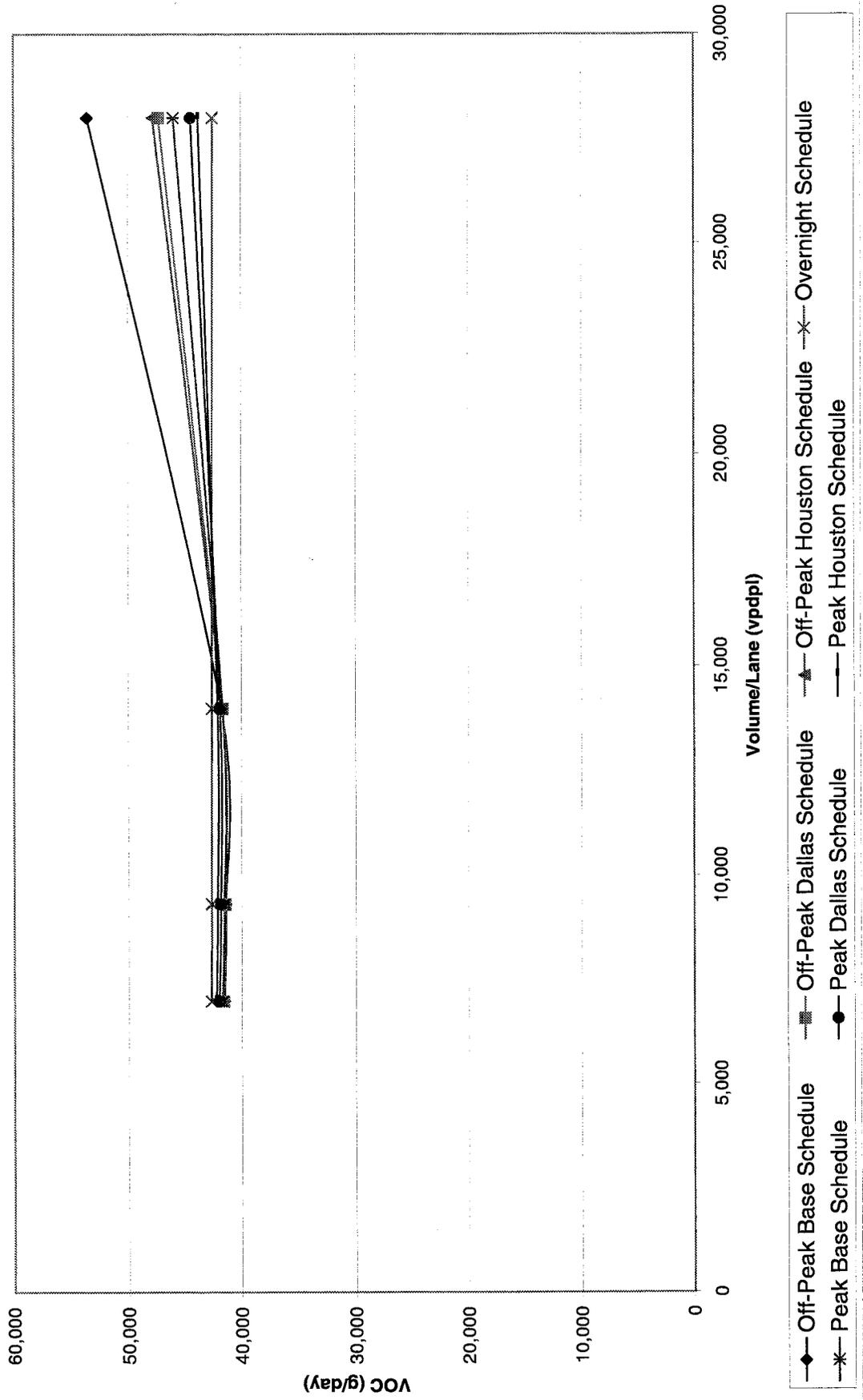


- ◆ Off-Peak Base Schedule
- Off-Peak Dallas Schedule
- ▲ Off-Peak Houston Schedule
- Peak Base Schedule
- Peak Dallas Schedule
- ◆ Overnight Schedule
- * Off-Peak Houston Schedule
- * Peak Houston Schedule

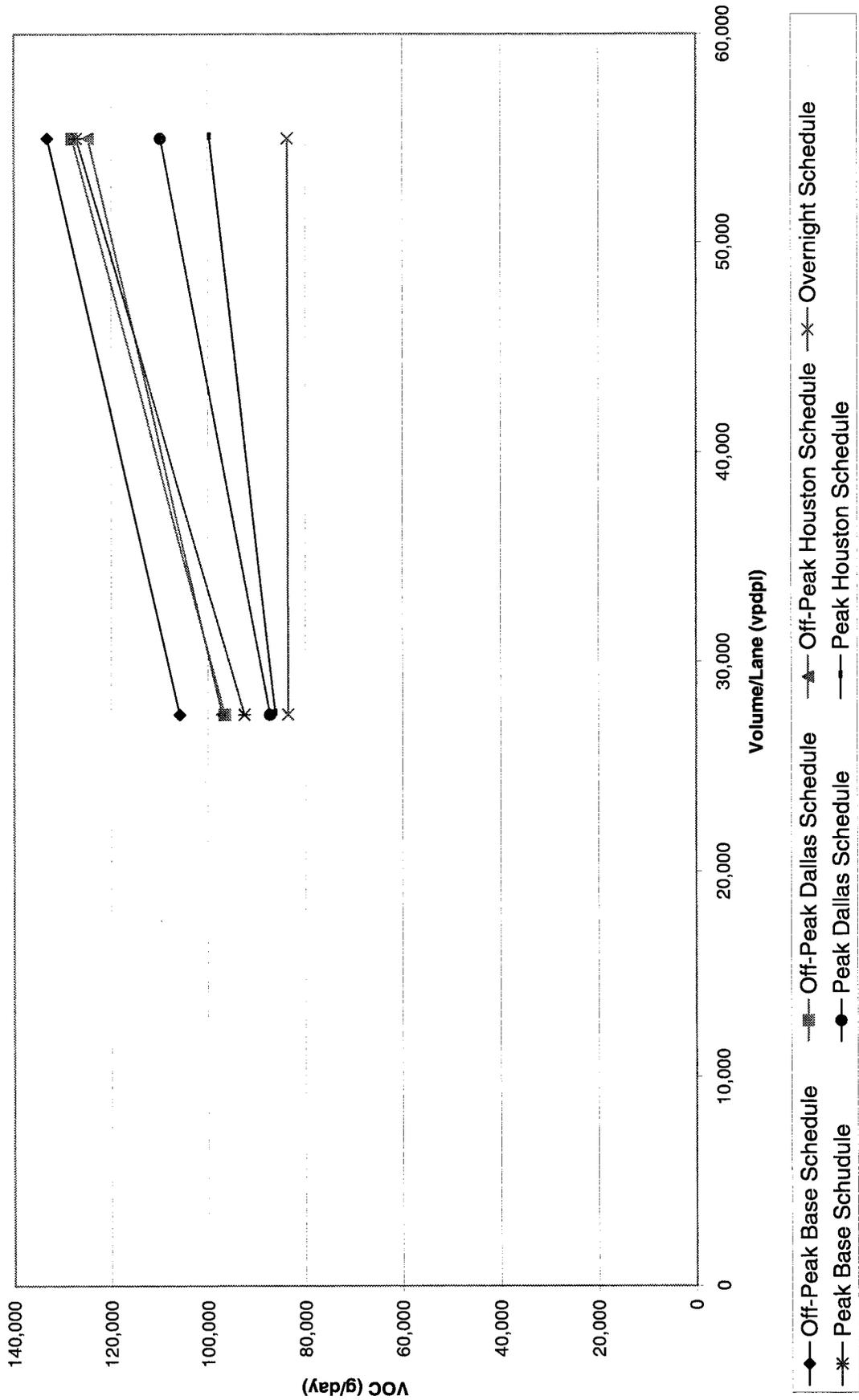
VOC for Low Volume Four-Lane Section



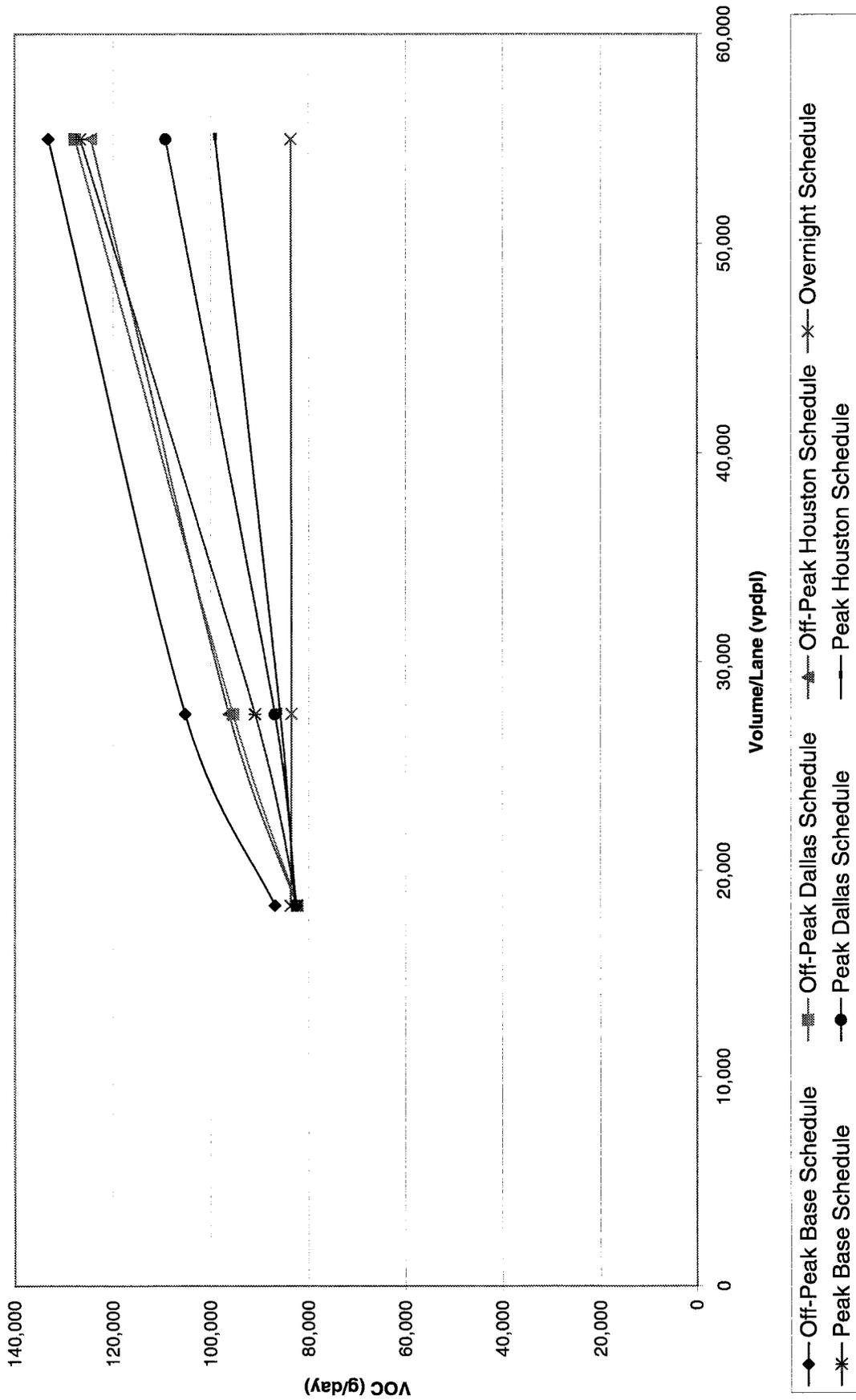
VOC for Low Volume Five-Lane Section



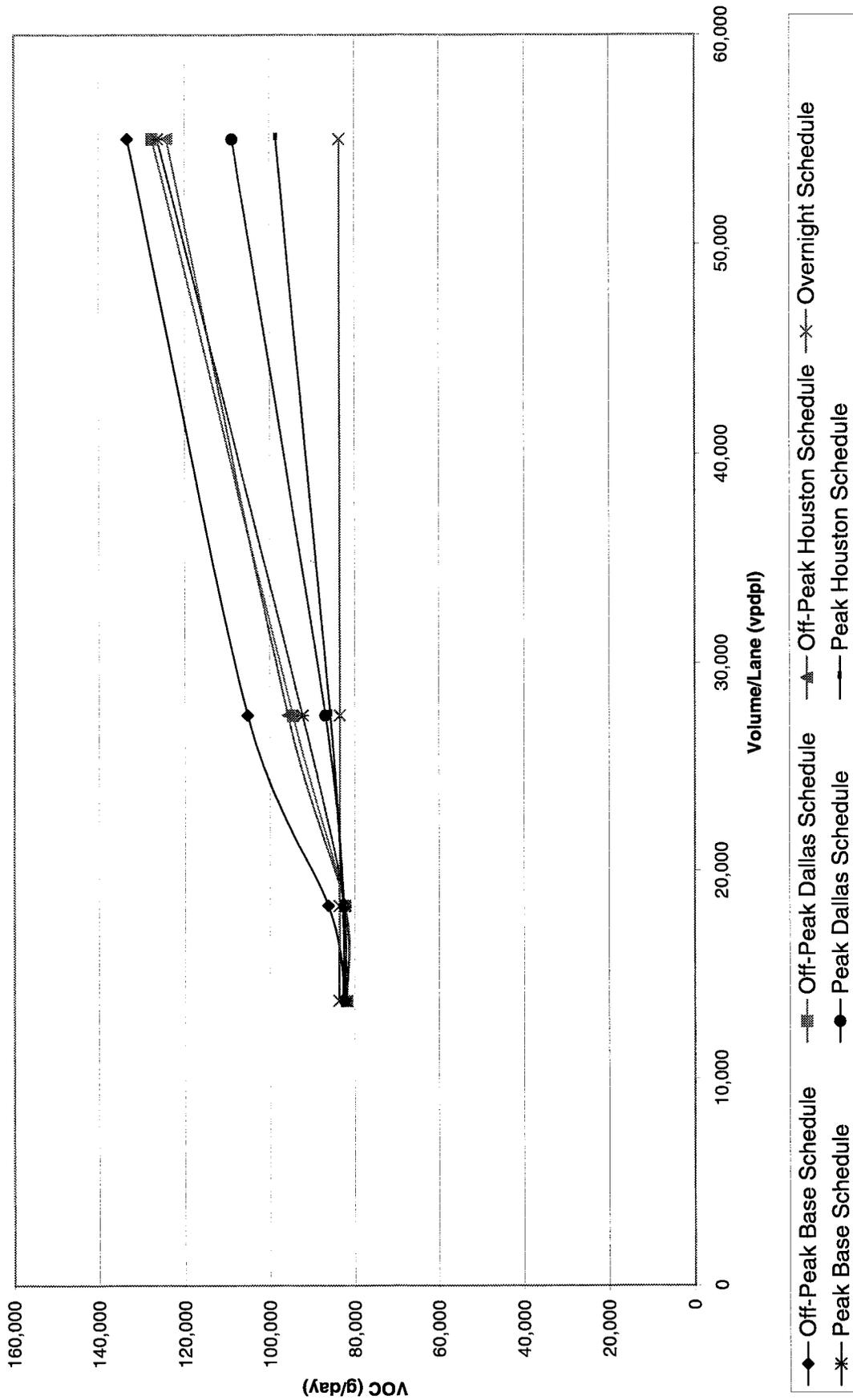
VOC for Medium Volume Three-Lane Section



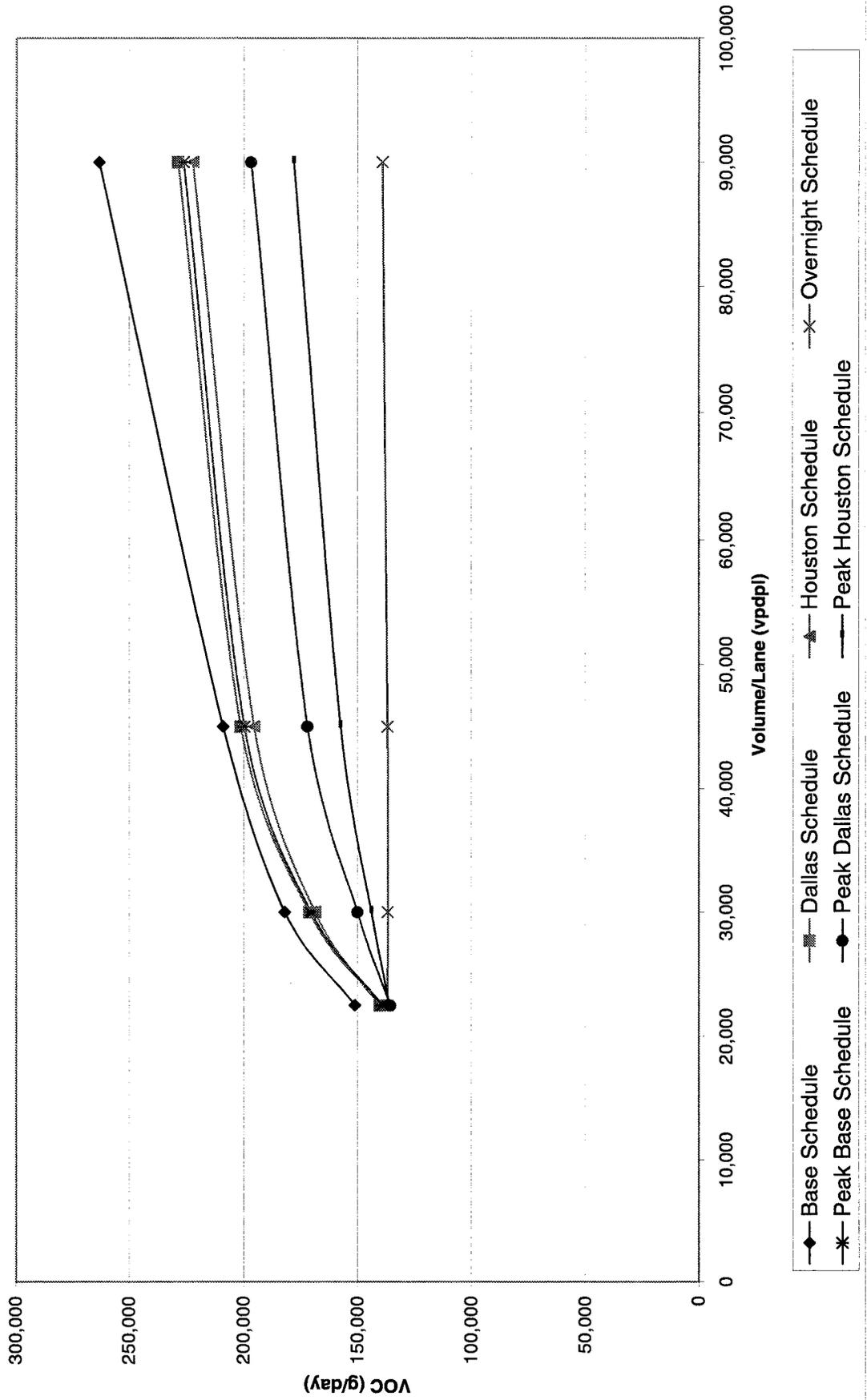
VOC for Medium Volume Four-Lane Section



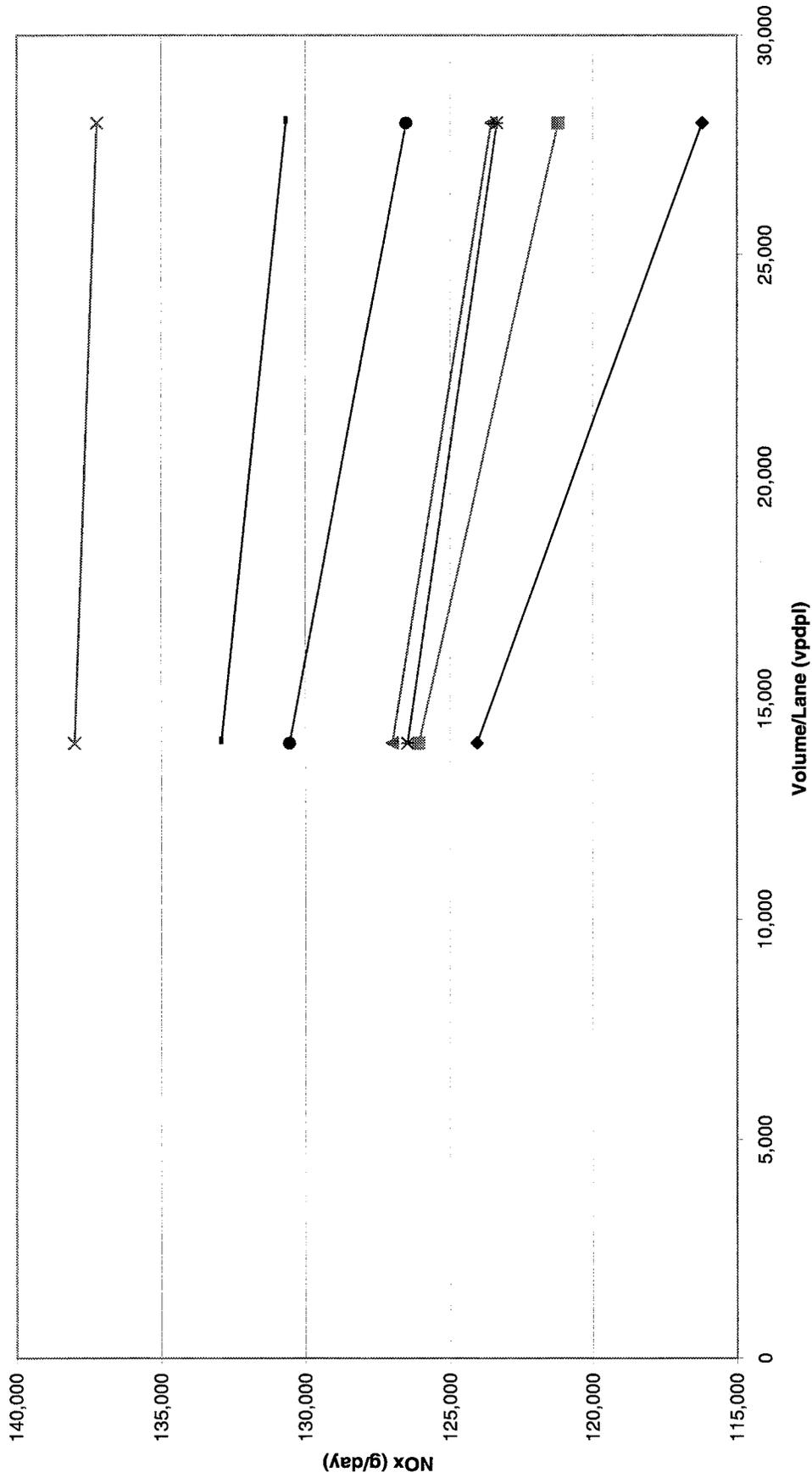
VOC for Medium Volume Five-Lane Section



VOC for High Volume 5 Lane Section

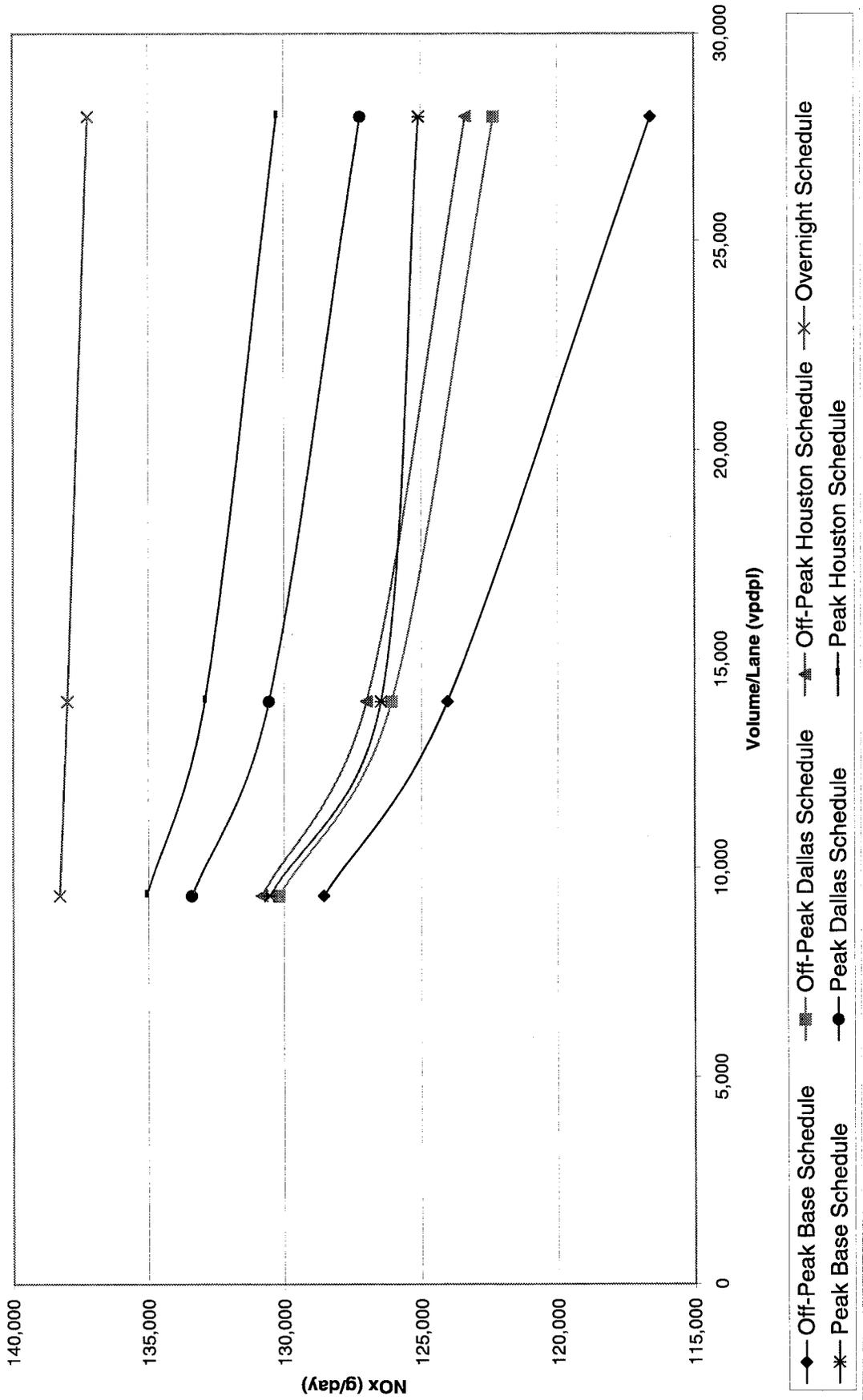


NOx for Low Volume Three-Lane Section

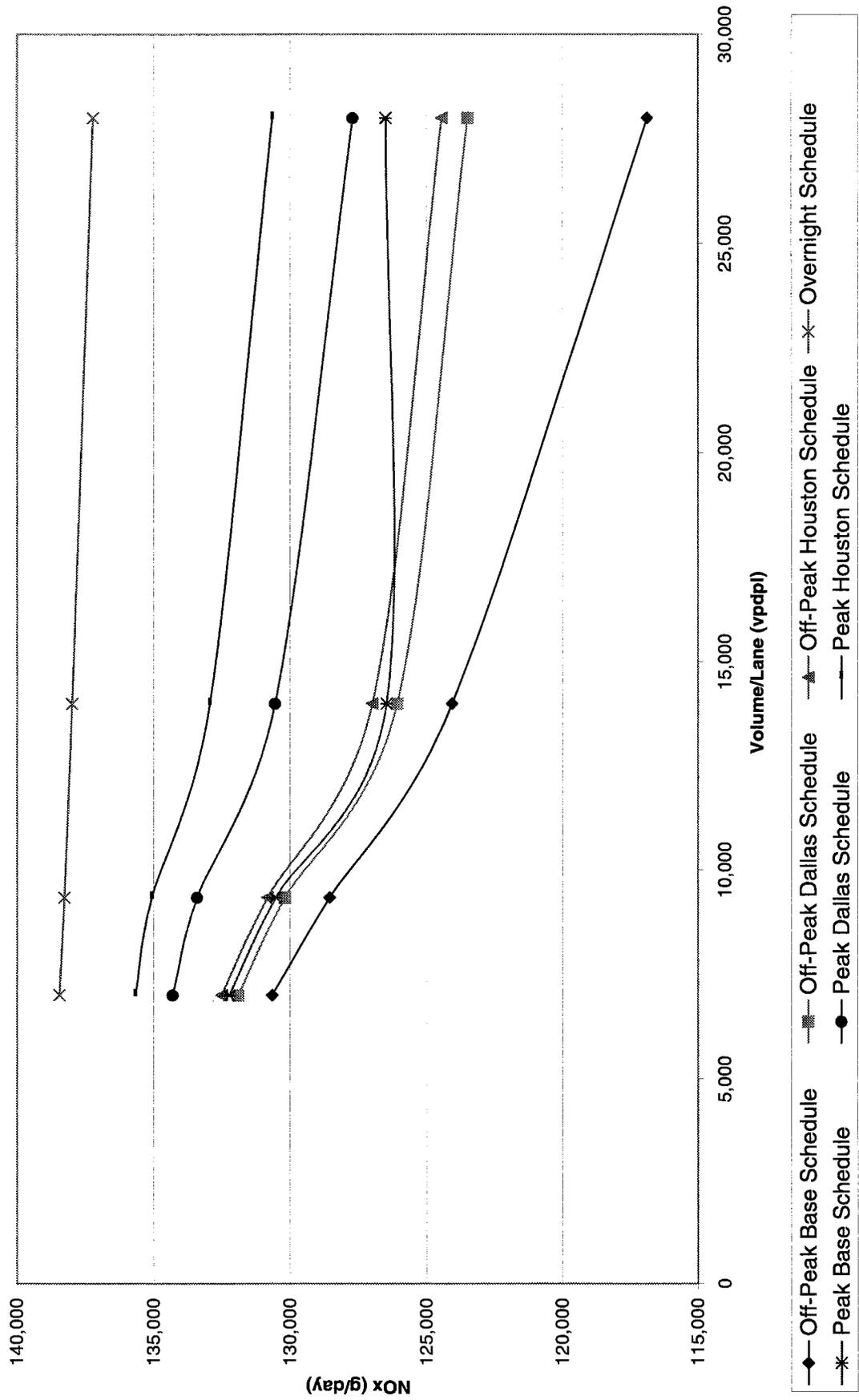


- ◆ Off-Peak Base Schedule
- ◆ Peak Base Schedule
- ▲ Off-Peak Dallas Schedule
- ▲ Peak Dallas Schedule
- ▲ Off-Peak Houston Schedule
- ▲ Peak Houston Schedule
- ✕ Overnight Schedule

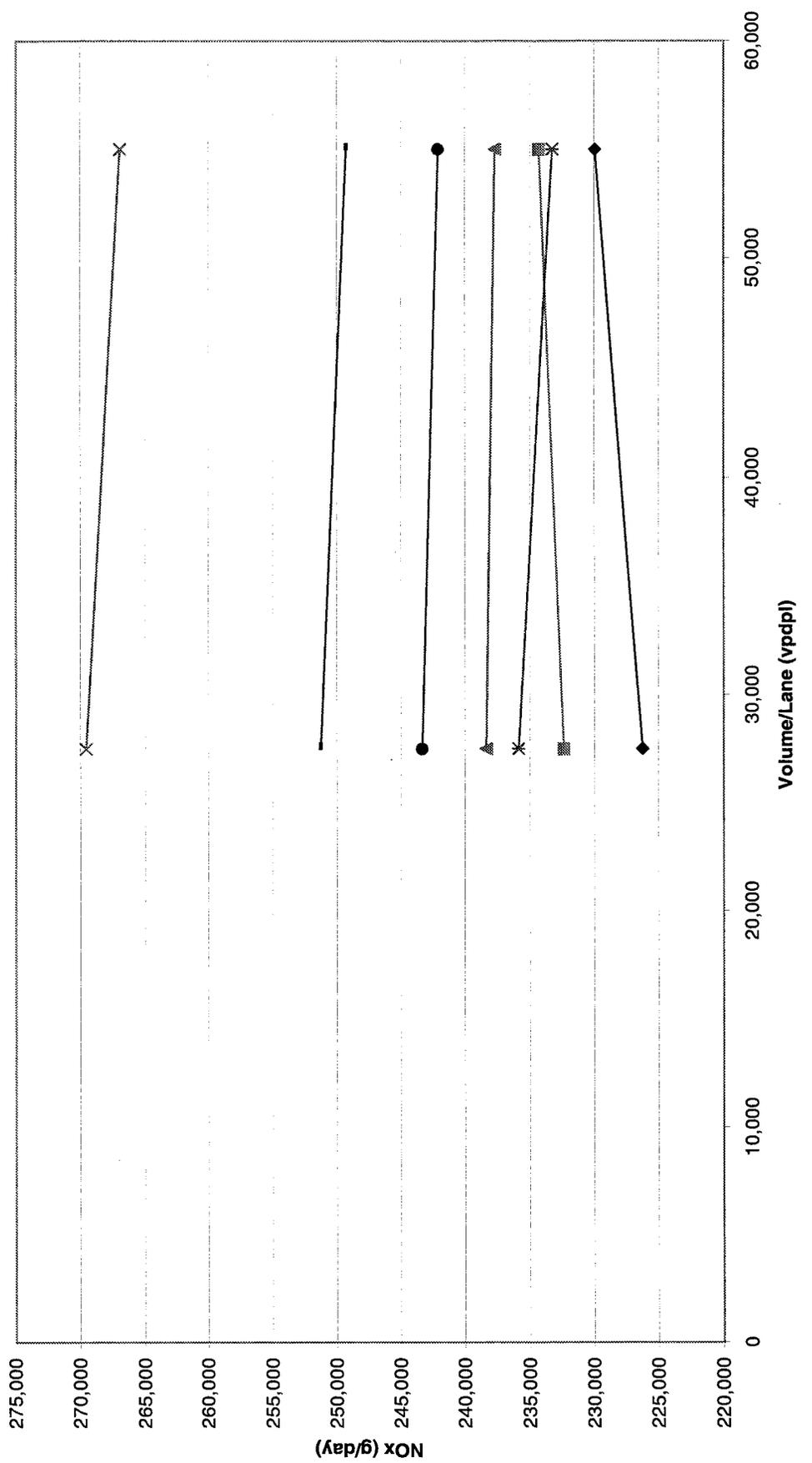
NOx for Low Volume Four-Lane Section



NOx for Low Volume Five-Lane Section

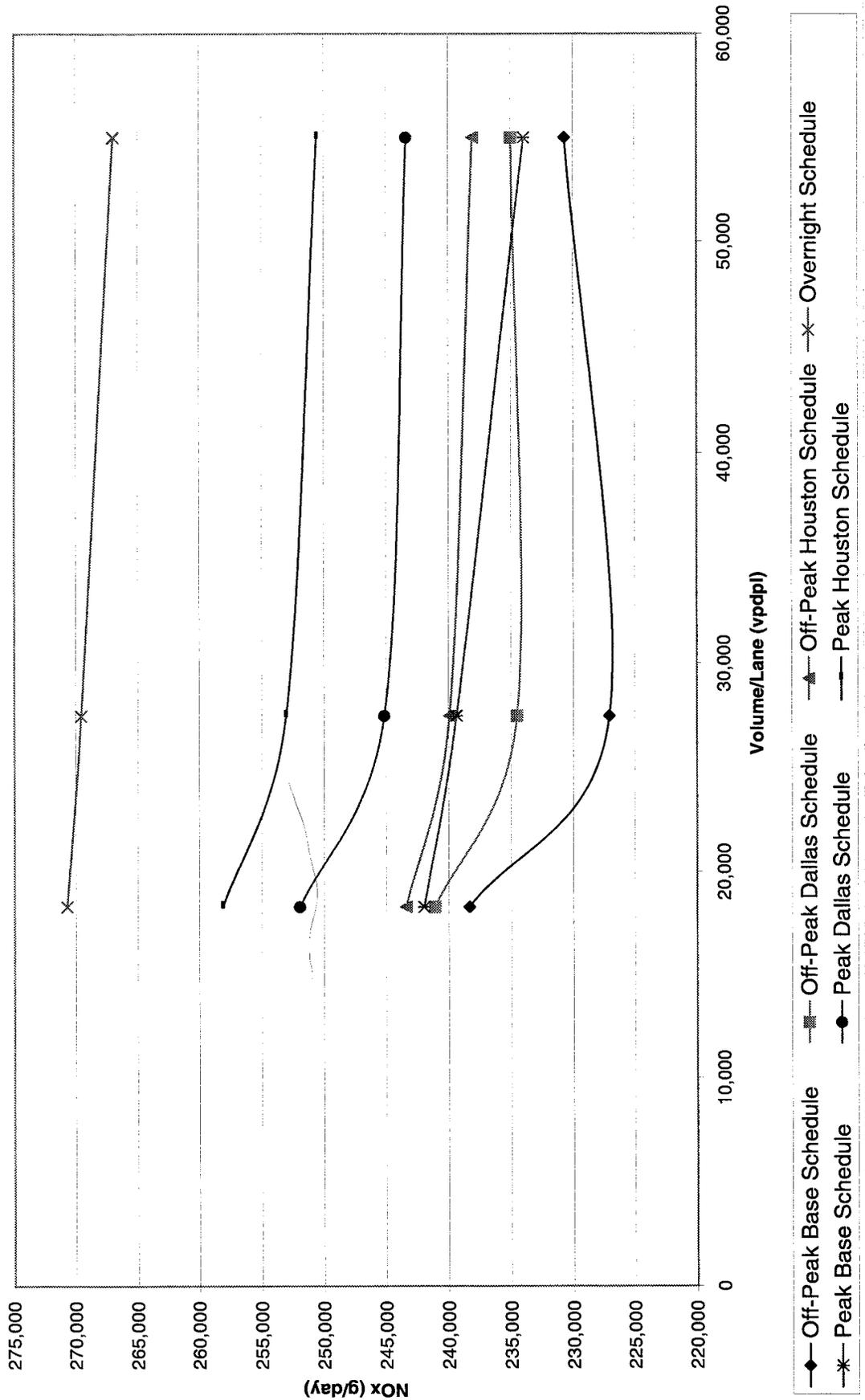


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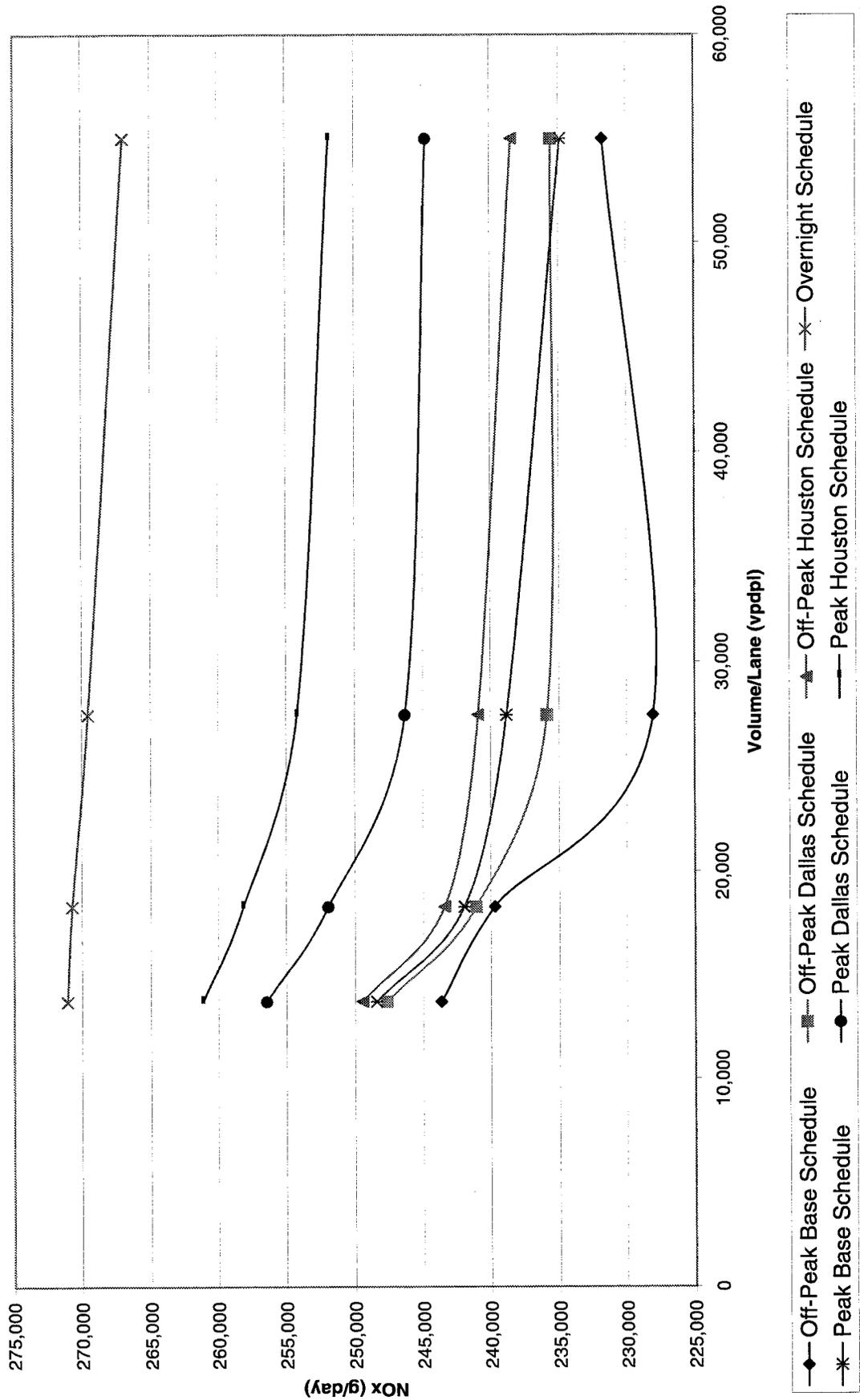


- ◆ Off-Peak Base Schedule
- ◆ Off-Peak Dallas Schedule
- ◆ Off-Peak Houston Schedule
- ◆ Overnight Schedule
- ◆ Peak Base Schedule
- ◆ Peak Dallas Schedule
- ◆ Peak Houston Schedule

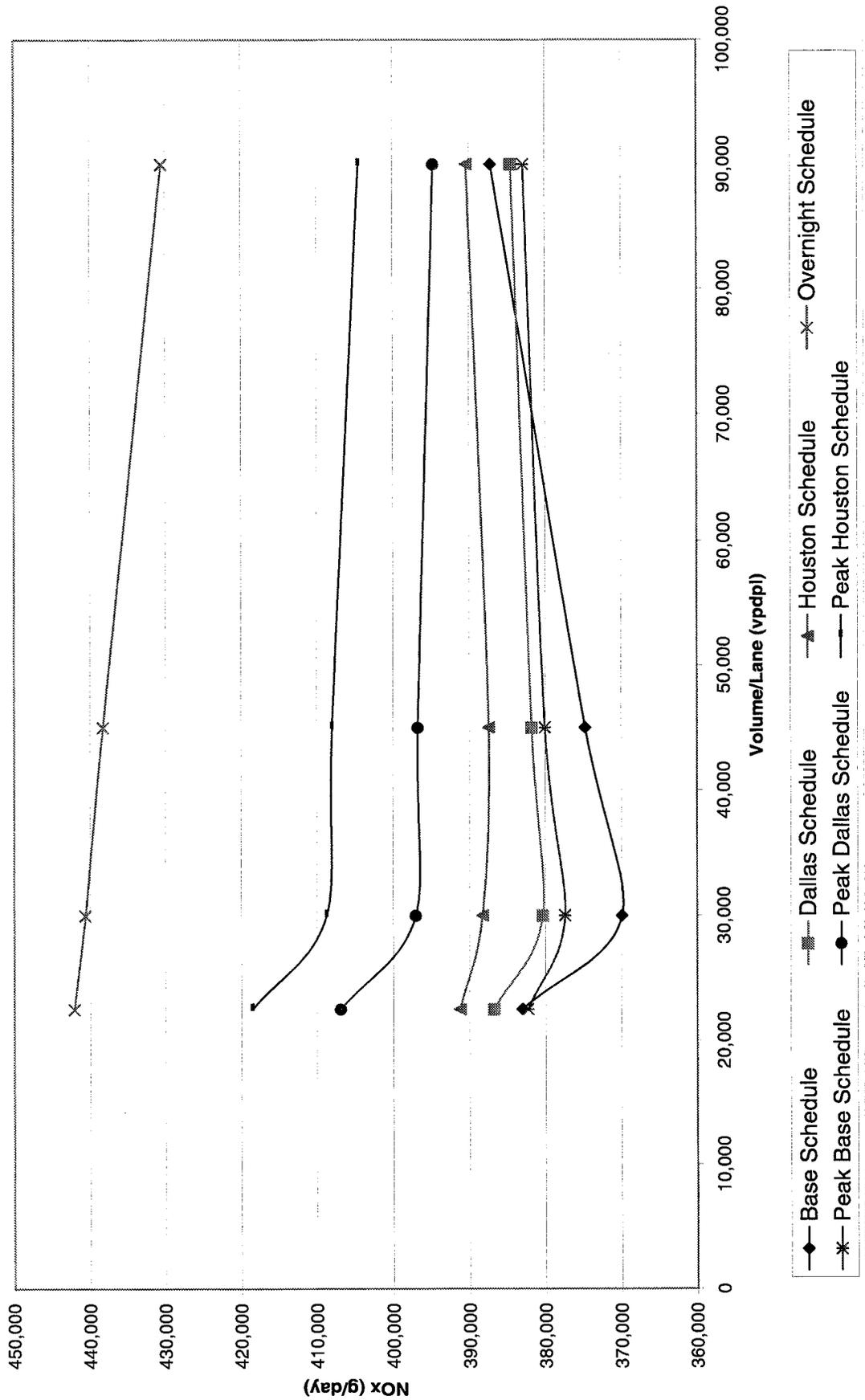
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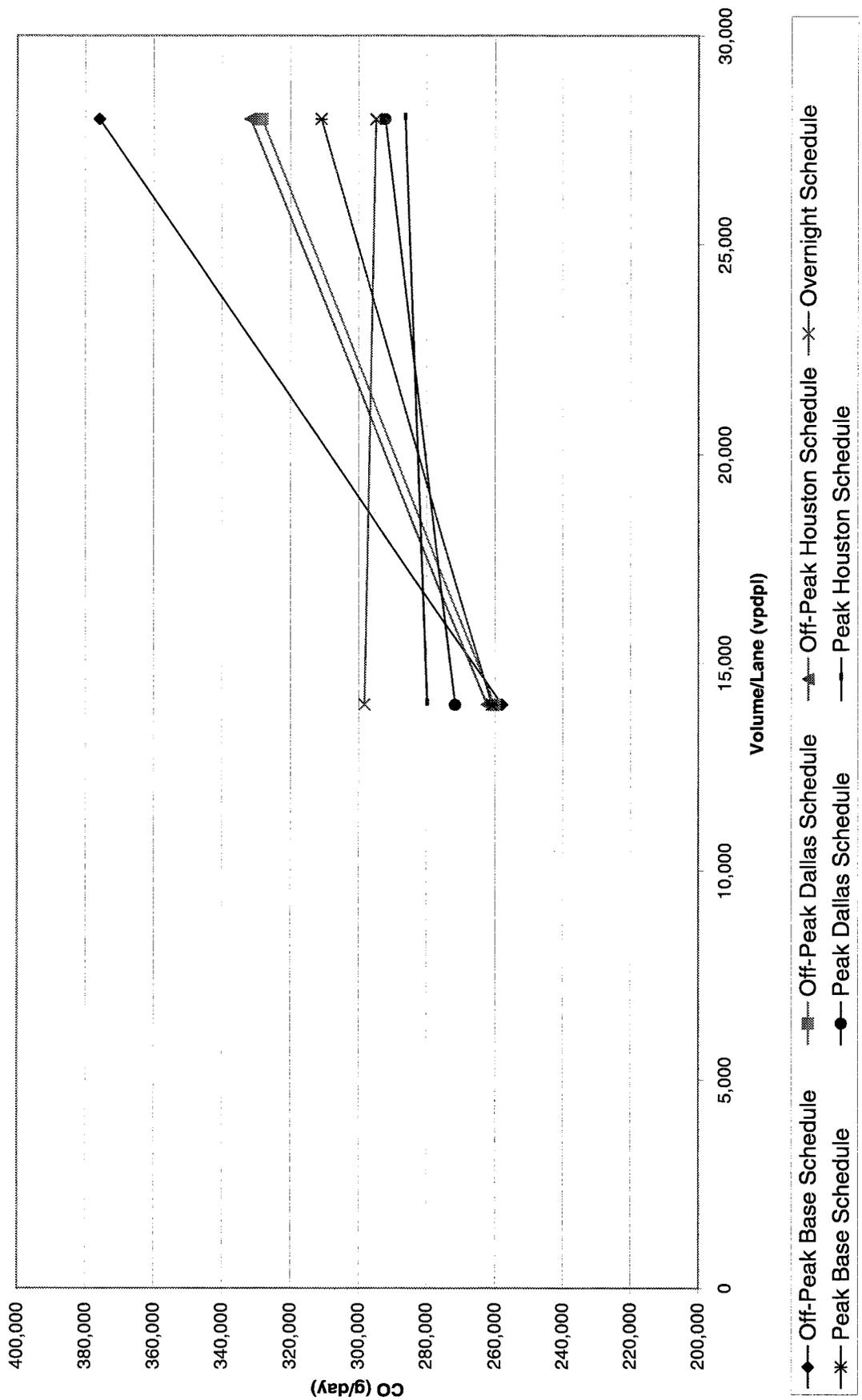
NOx for Medium Volume Five-Lane Section



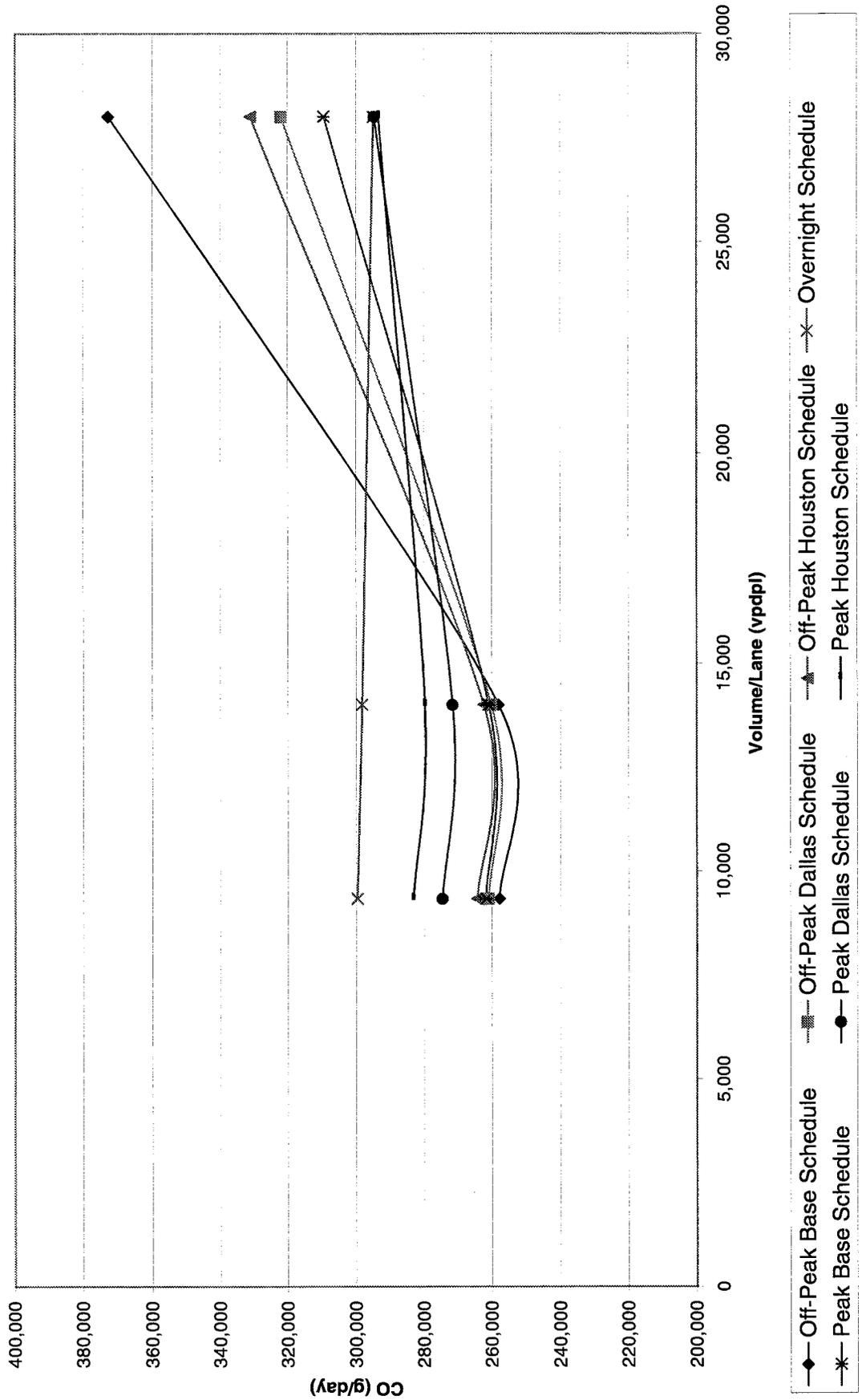
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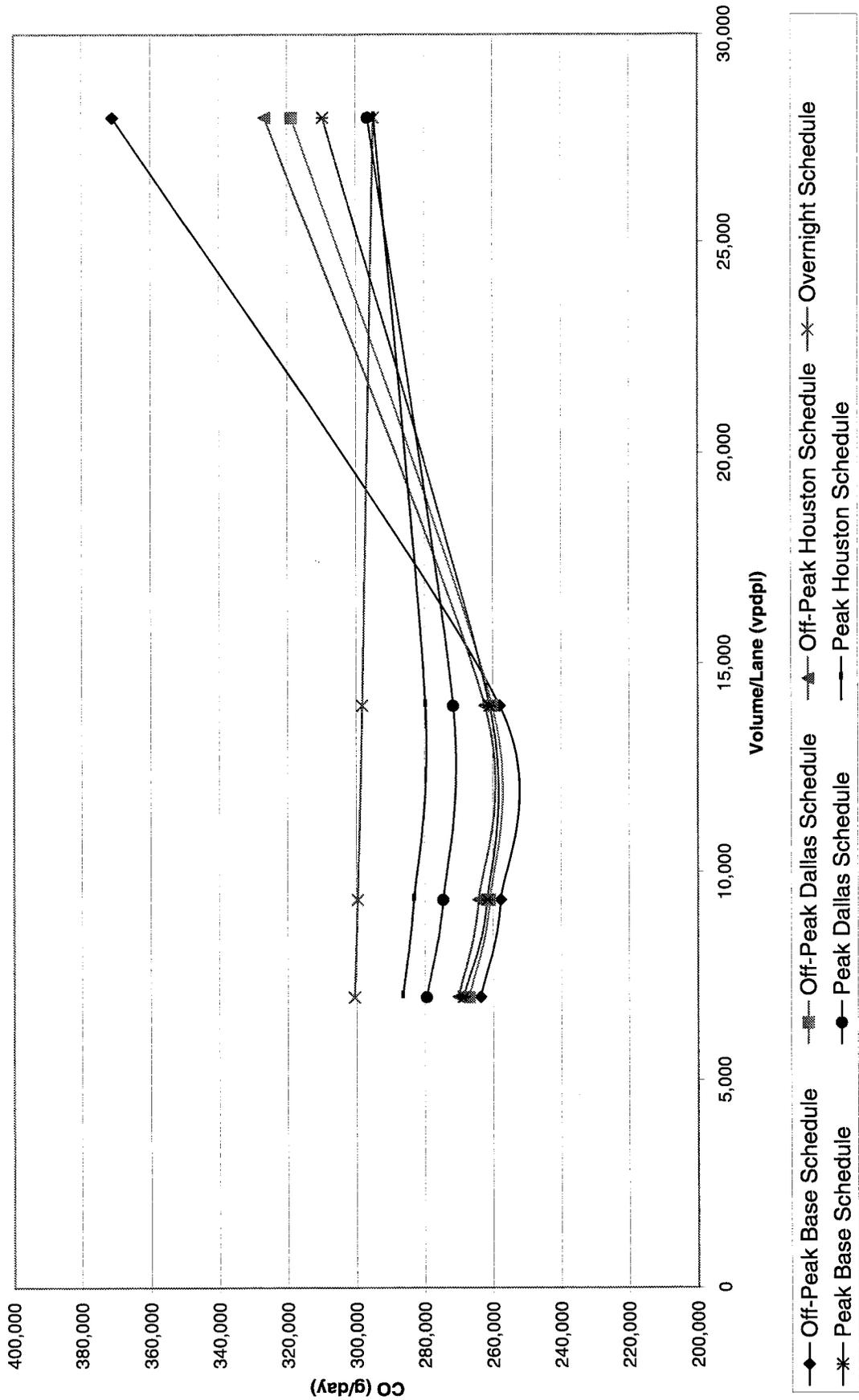
CO for Low Volume Three-Lane Section



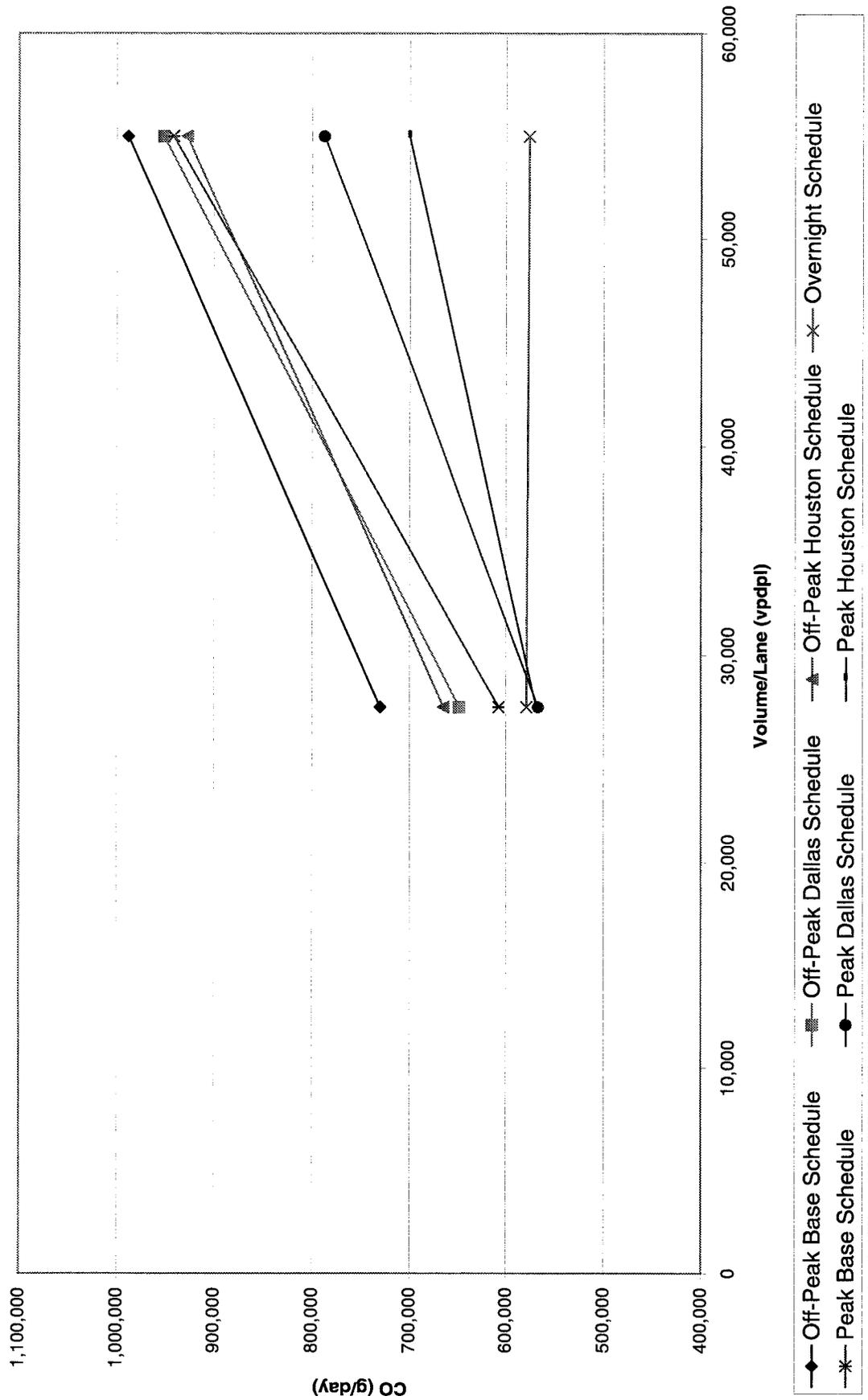
CO for Low Volume Four-Lane Section



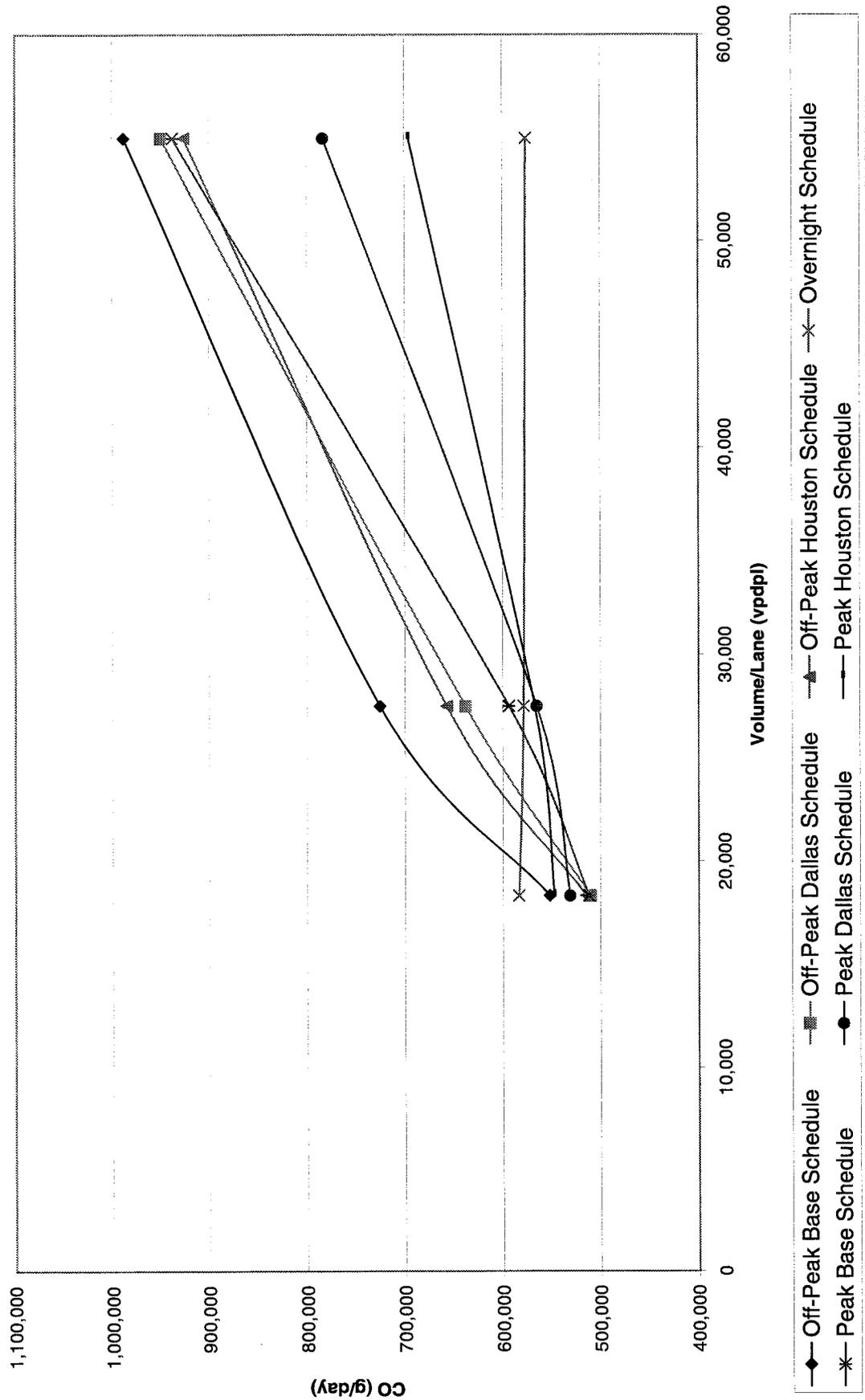
CO for Low Volume Five-Lane Section



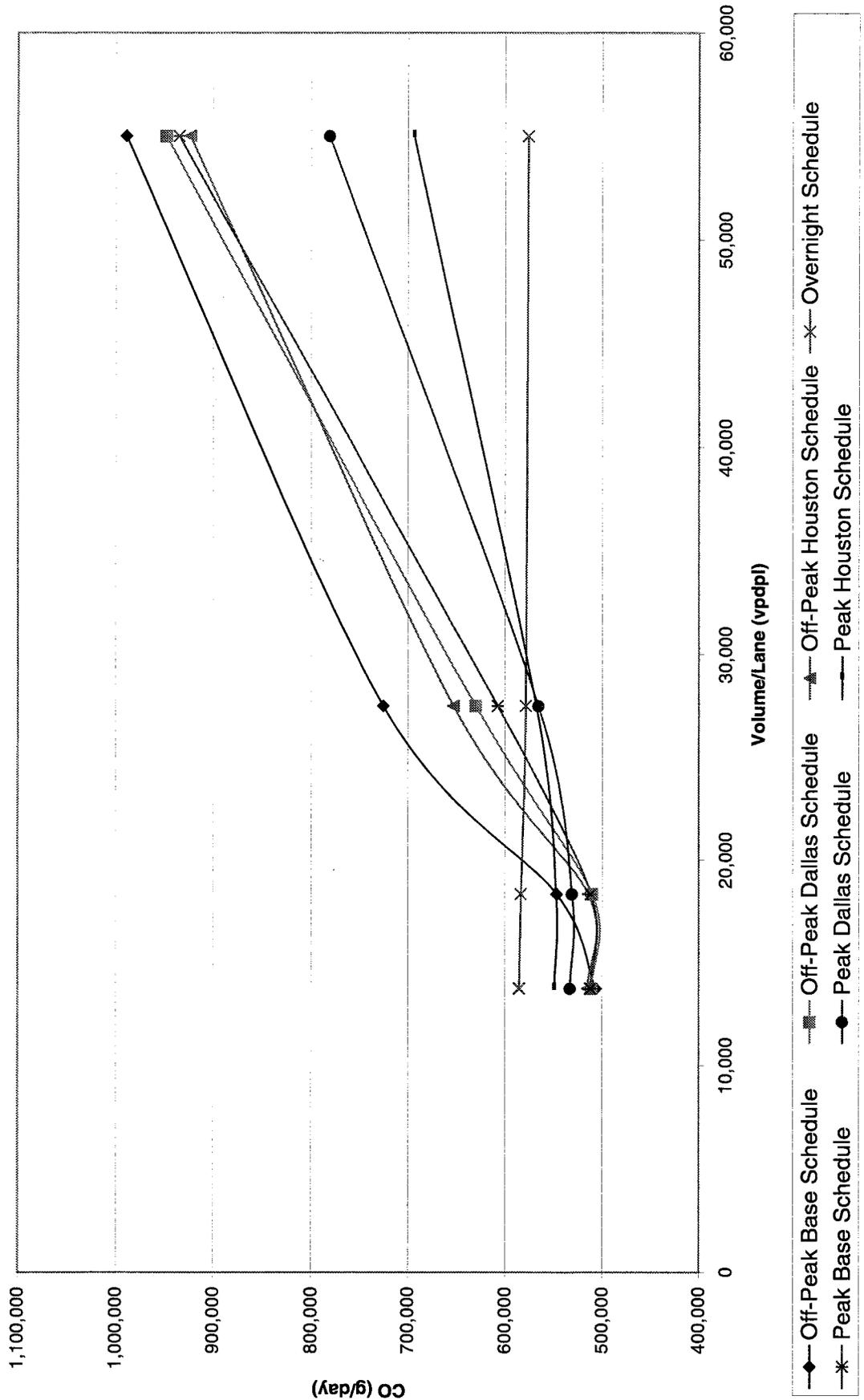
CO for Medium Volume Three-Lane Section



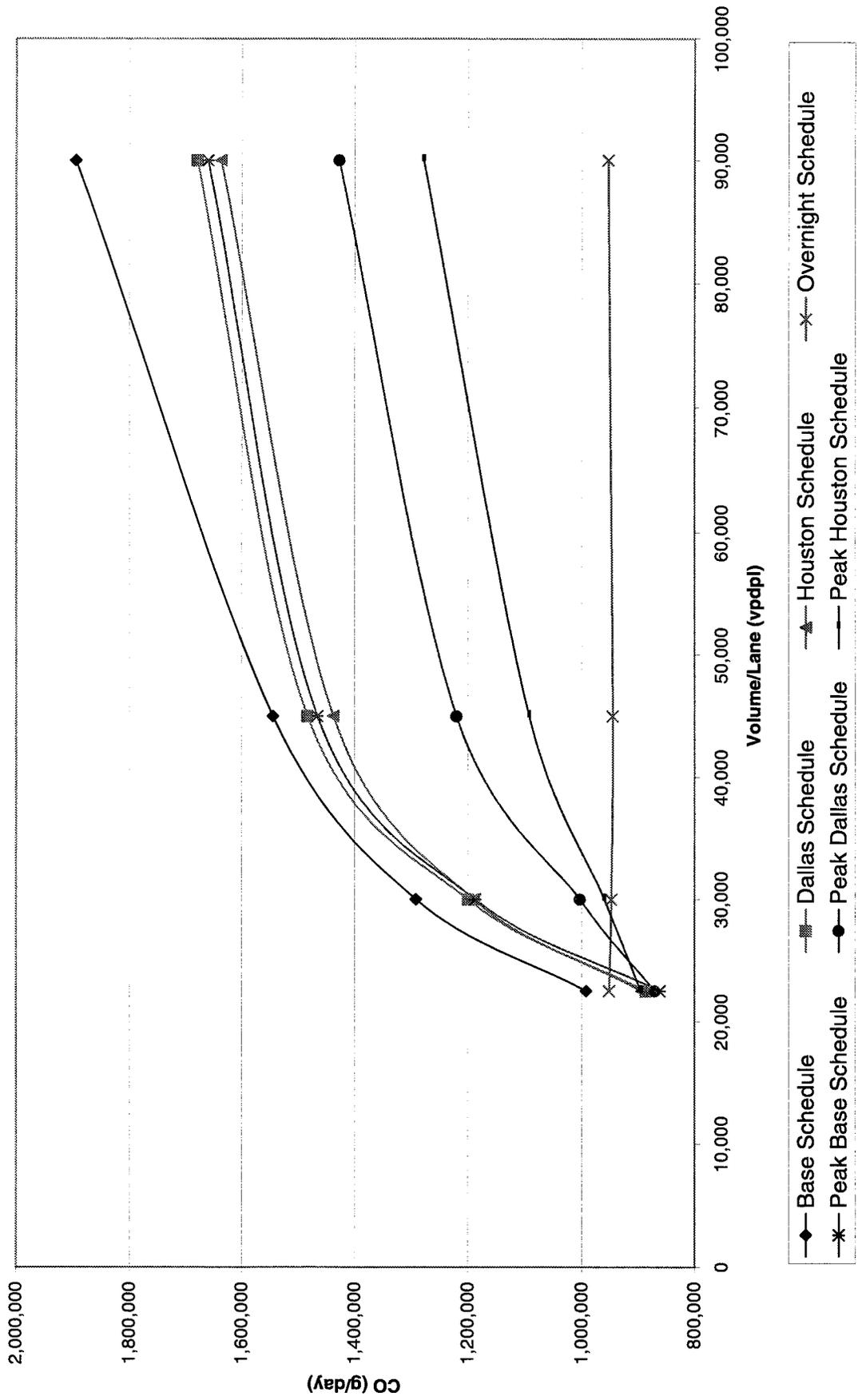
CO for Medium Volume Four-Lane Section



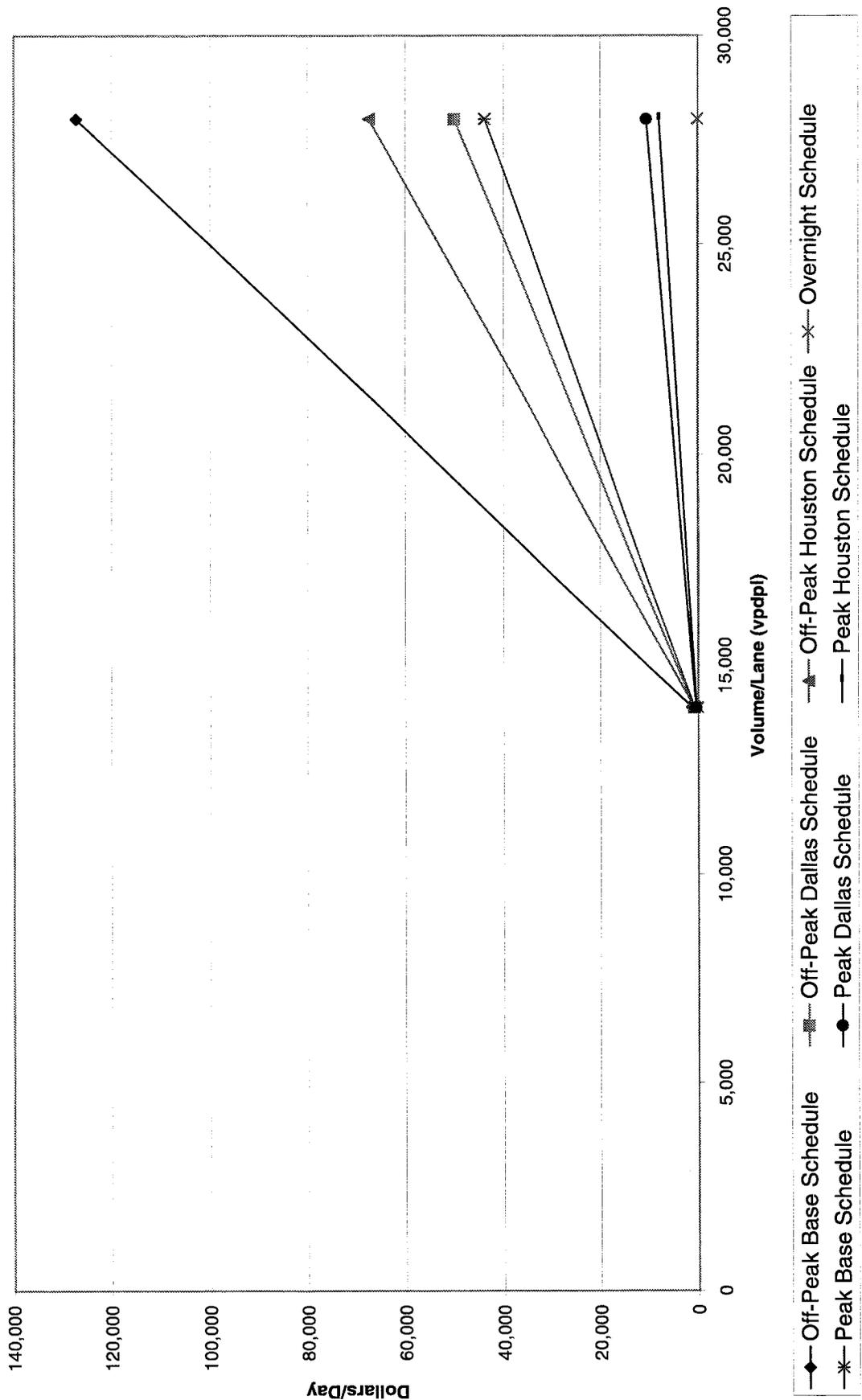
CO for Medium Volume Five-Lane Section



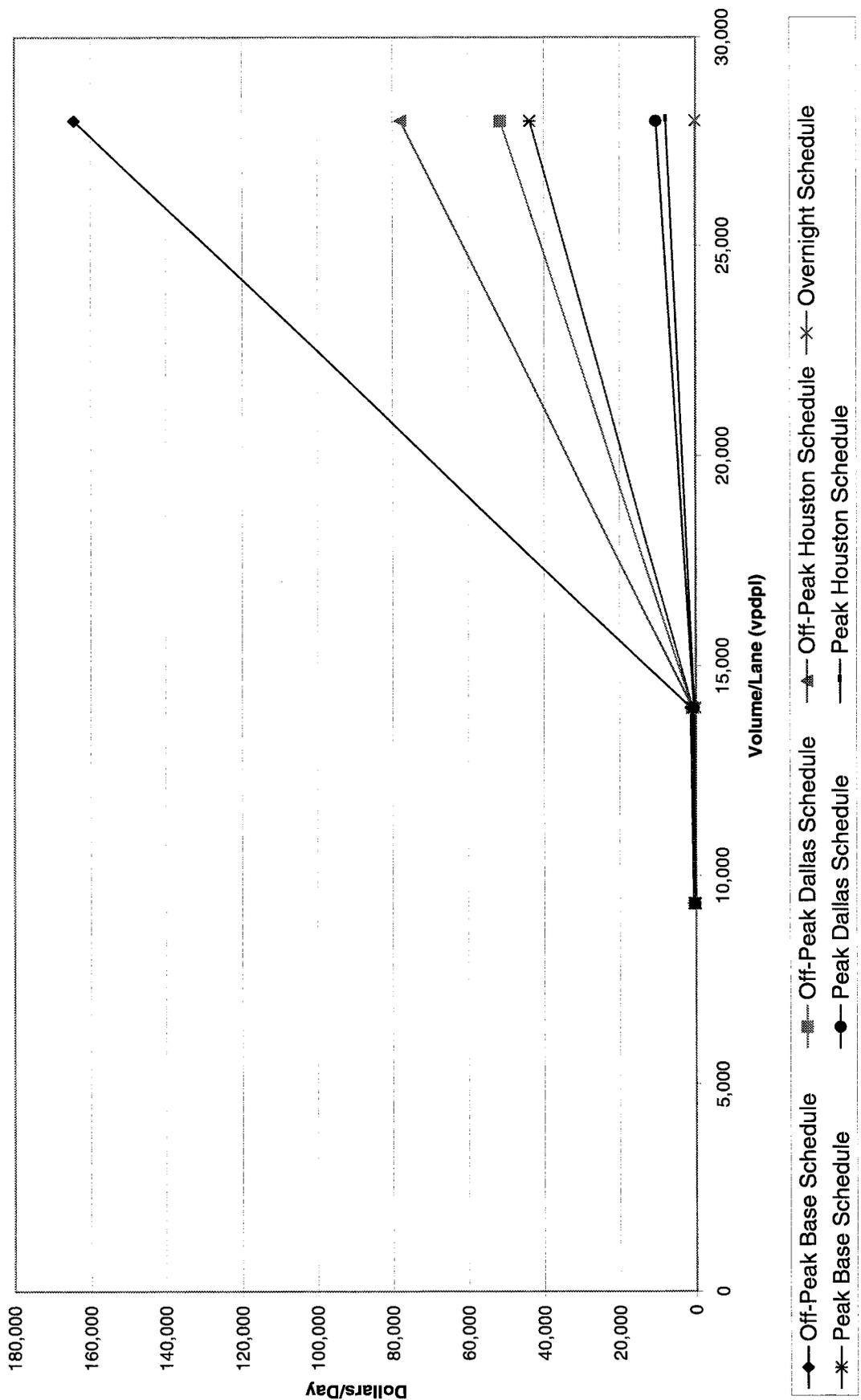
CO for High Volume Five-Lane Section



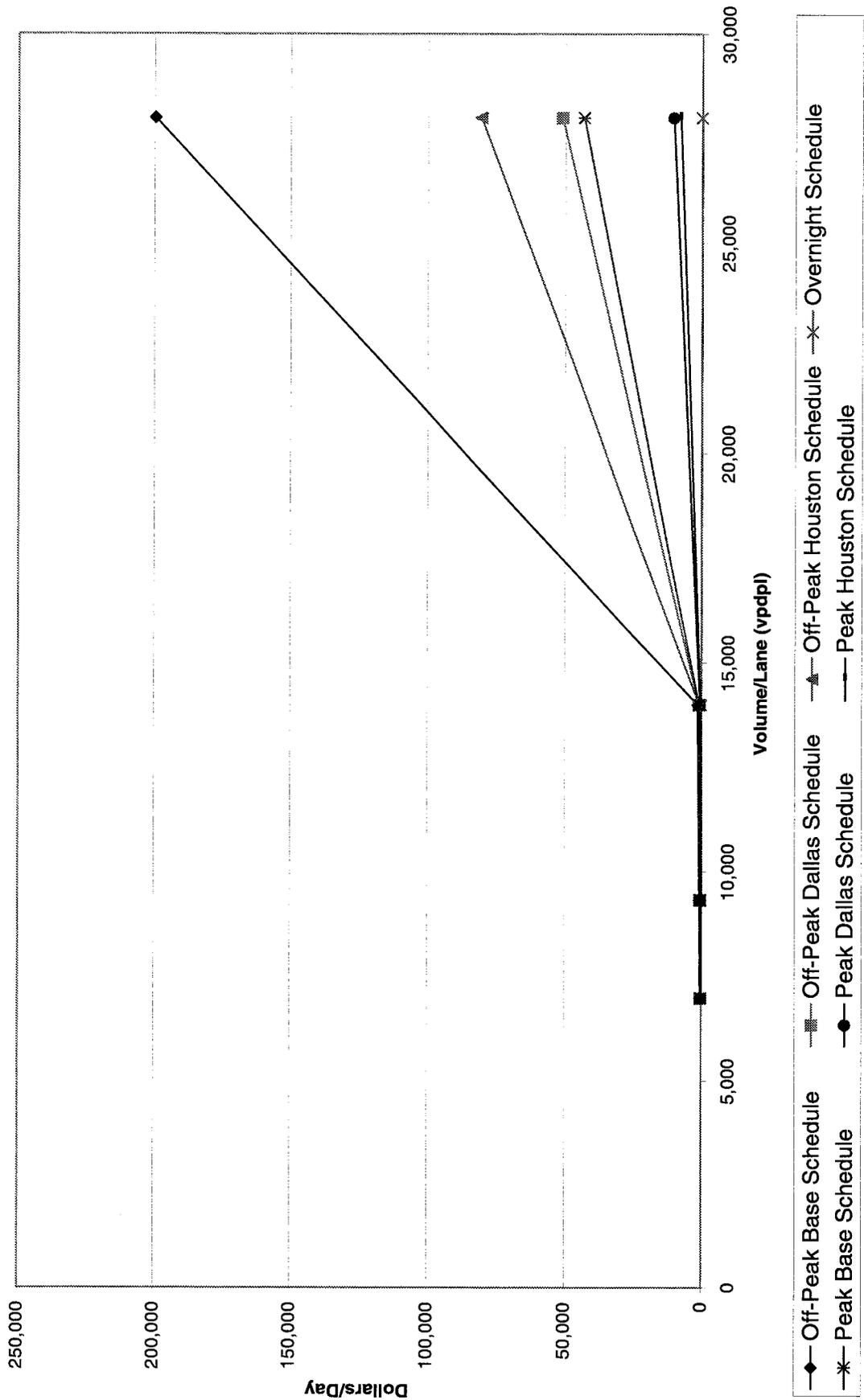
Road User Cost for Low Volume Three-Lane Section



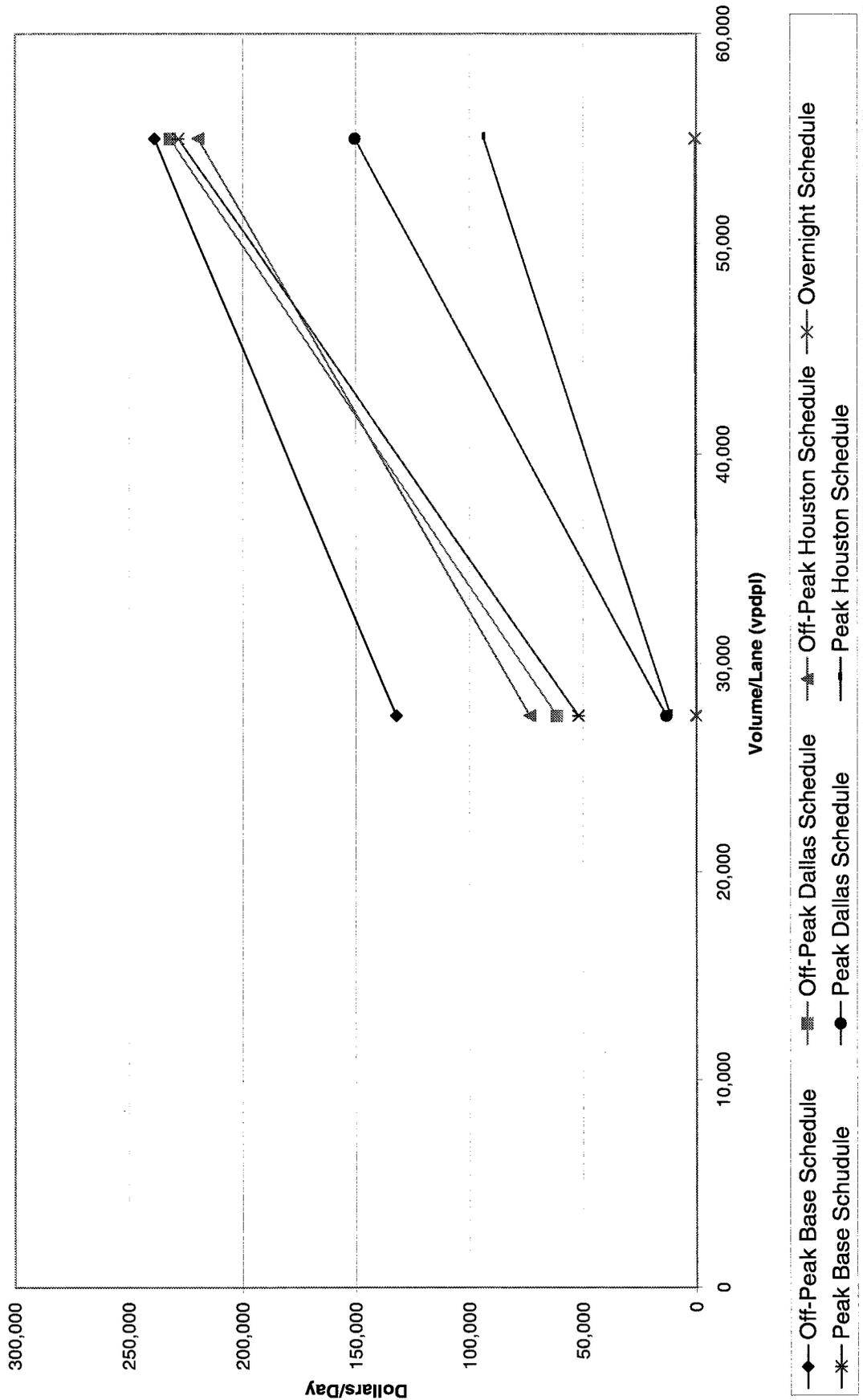
Road User Cost for Low Volume Four-Lane Section



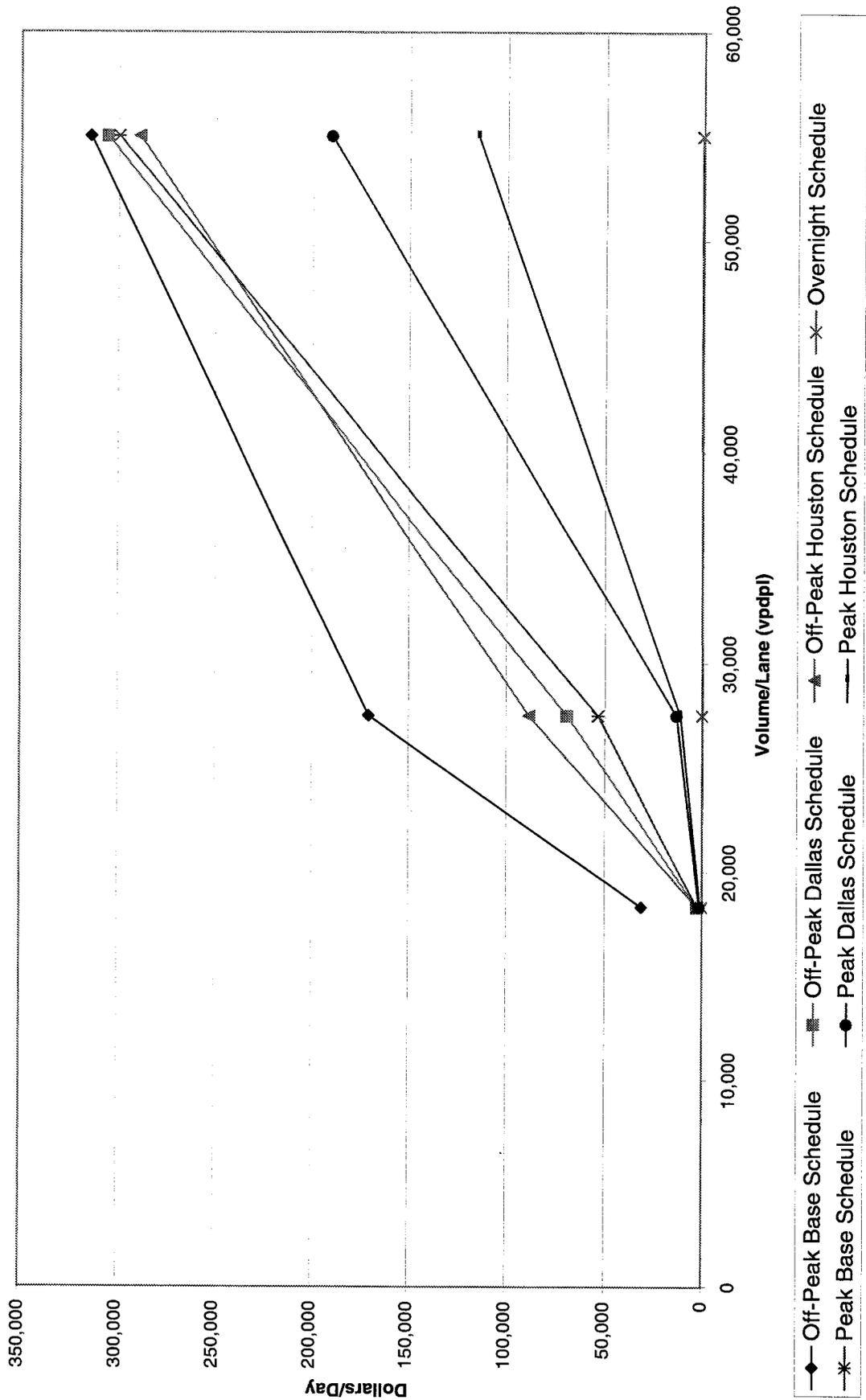
Road User Cost for Low Volume Five-Lane Section



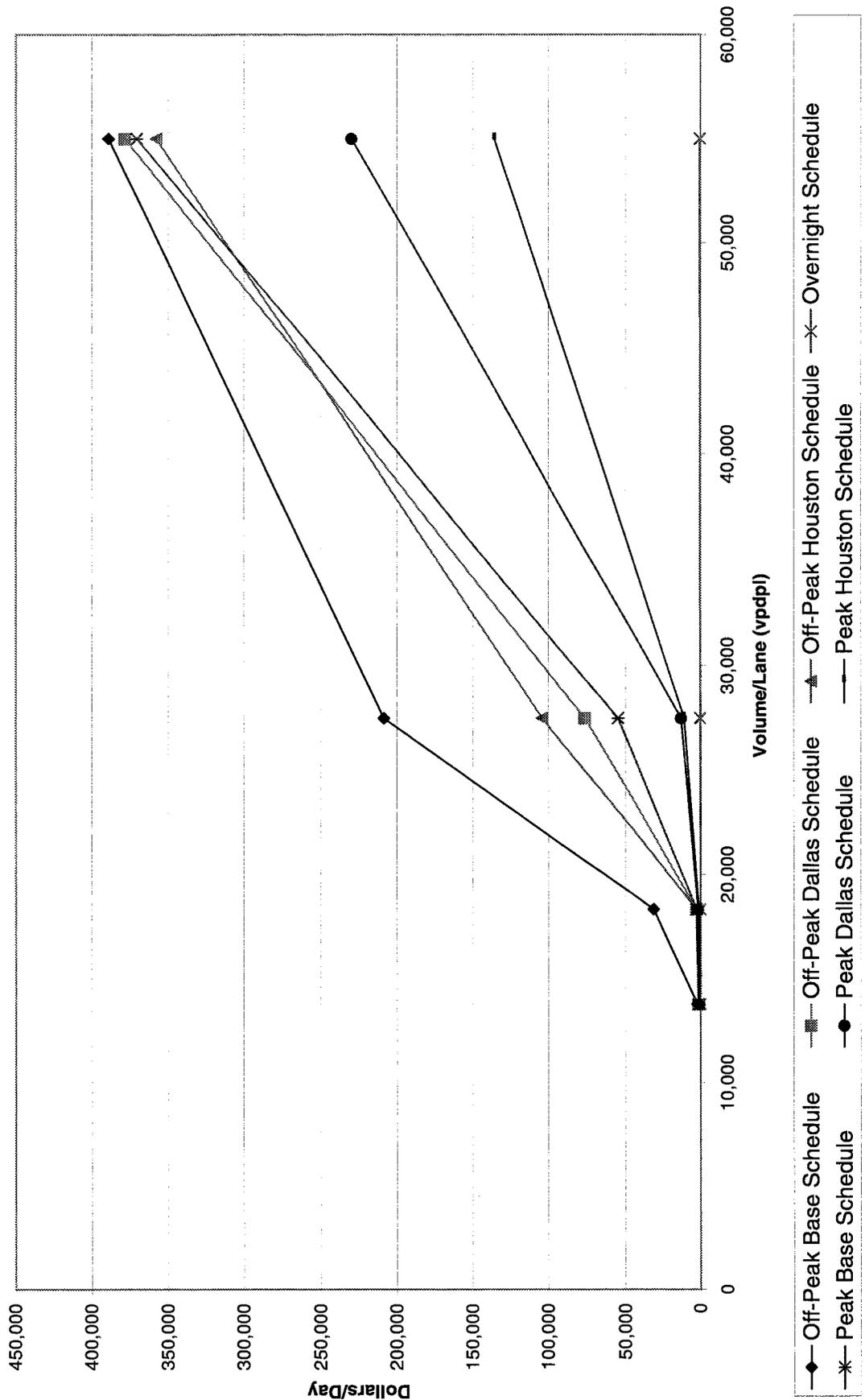
Road User Cost for Medium Volume Three-Lane Section



Road User Cost for Medium Volume Four-Lane Section



Road User Cost for Medium Volume Five-Lane Section



Road User Cost for High Volume Five-Lane Section

