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CONTAMINANT LEVEL CONTROL IN PARKING GARAGES

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1.0 INTRODUCTION

This paper presents the results of a research program that was conducted for ASHRAE by TRC-Environmental Consultants, Inc. The purpose of the study was to provide information on the effectiveness of existing ASHRAE ventilation guidelines for maintaining acceptable air pollutant levels and to develop a methodology for including economic utilization of energy in the consideration of future guidelines.

Ventilation requirements for enclosed parking garages are currently expressed in terms of flow rate per unit of floor area or in air volume changes per unit time. Such guidelines are based on assumptions about ventilation system flow rates, motor vehicle emissions, traffic patterns and resulting carbon monoxide (CO) concentrations. This program was based on measurement of all these parameters at several underground parking garages. Data analysis included a review of pertinent literature and development of simple mathematical models for ventilation assessment.

This study has focused on carbon monoxide (CO). Other pollutants such as sulfates, oxides of nitrogen and odorous compounds also affect air quality, but CO is universally associated with garage operation and is generally seen as the major health factor.

2.0 CONCLUSIONS AND RECOMMENDATIONS

1. Ventilation systems designed to meet ASHRAE's existing guidelines provide adequate air quality with respect to the allowable OSHA carbon monoxide concentration.

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All underground parking facilities studied were found to have better air quality than required by the current OSHA standards. However, substances other than carbon monoxide, such as smoke and soot, fuel vapors, and odor causing compounds, may require additional analysis before appropriate guidelines can be established for adequate air quality in parking garages. Odor causing compounds may be of special concern, from the standpoint of public acceptability, since the concentration of such compounds sufficient to cause complaint or even physical effects such as nausea is far lower than a hazardous concentration of CO. In addition, the effect of malodorous fumes does not depend on long-term, time-weighted averages.

Ventilation system design guidelines should consider factors in addition to time-weighted averages of carbon monoxide concentration alone.

2. Significant energy savings can be achieved by operating ventilation fans in a way which matches the use pattern of the garage in which they are installed.

Most parking facilities have readily predictable periods of greater or lesser activity. Utilizing such information to schedule fan operation can result in a considerable reduction in overall energy use. Even if conservative safety factors are included to account for possible variations in the emissions, energy savings can be achieved without the need for complex air quality monitoring control systems. The ability to modify or override such pre-scheduled operation is necessary to handle unusual or unforeseen circumstances. However, many garages could utilize a pre-scheduled system and easily maintain acceptable air quality.

Design guidelines should include specific methodologies to determine fan operation schedules.

3. Position of air supply and exhaust ducts relative to each other, to building design and to traffic flow patterns has a major impact on ventilation system efficiency.

Ventilation systems that are designed only to move the recommended volume of air in and out of a parking facility may not provide efficient ventilation. Factors such as "short circuiting" or channeling between supply and exhaust points, obstructions to air flow, thermal stratification, re-entrainment of contaminated discharge air into the supply system, and emission "hot spots" with inadequate ventilation can adversely affect air quality.

Design guidelines should address system geometry as well as capacity.

4. Automobile emissions are highly variable from vehicle to vehicle and even for the same vehicle at different times.

Air quality in enclosed parking facilities can be significantly affected by a relatively small number of exceptionally "dirty" vehicles. Unexpectedly high, short-term local concentrations of CO, hydrocarbons and smoke or haze can result. While such short-term fluctuations are not always significant in terms of time-weighted average exposures, they can result in a negative public perception of air quality.

Design guidelines should consider emission variability as well as the average emission rate when recommending ventilation requirements and safety margins.

3.0 METHODOLOGY

3.1 Literature Search

A literature search was performed to identify available technical literature concerning motor vehicle emissions under a variety of operating conditions. Information reviewed included CO, HC, and NO_x emissions under cold and warm start conditions; engine idling, accelerating, decelerating; and seasonal and altitude effects. An Appendix to the full report contains references to some of the most applicable material that was found. The EPA Mobil 1 Emission Factor Model (1978) was found to be particularly useful and formed the basis for subsequent emissions estimates.

Literature concerning guidelines for ventilation design in parking garages was not extensive, and was found to be adequately summarized in the existing ASHRAE handbooks.

3.2 Site Selection Criteria

A major goal of the field test program was to observe the performance of a variety of underground garage ventilation systems built to present design criteria. Garages with distinctly different ventilation and floor layout designs and with a variety of different operating conditions were sought. Factors of special importance included: traffic flow patterns, types of vehicle traffic, ventilation rate schedules, elevation and seasonal temperature differences.

3.3 General Description of Sites

Multiple-level underground parking garages at three separate geographical locations were selected for field testing. These sites included two parking levels in a garage in Hartford, CT; two parking levels in a parking facility in Denver, CO; and one parking level at a location in Los Angeles, CA. The two parking levels at the Hartford, CT location were tested in both the summer and winter. The others were tested only during warm weather. If the different garage levels and seasonal tests are considered independently, a total of seven garage settings was investigated.

Fig. 1 presents a schematic view of the garage sites studied, and a general plan of CO monitoring points.

The Hartford bi-level ventilation systems were operated on a schedule which roughly matched the morning and afternoon rush hours. In Hartford A, nearly all traffic on the level occurred during rush hour periods. Hartford B had a moderate lunchtime traffic load as well. All traffic consisted of light-duty vehicles operating at near sea-level conditions.

A constant ventilation rate was supplied at the Denver sites at all times. Ventilation air was supplied at a mid-level height and exhausted at both high and low level heights. Denver A was used for commuter employee parking. Denver B was used exclusively for company fleet vehicles (mostly passenger autos and light-duty vans). Peak traffic hours were not as extreme as at the Hartford site due to staggered work shifts. The traffic in Denver A also included pass-through traffic from Denver B, the level below. Denver B had the interesting property of having its peak emissions load during the morning traffic period instead of the afternoon. Most traffic on this level in the morning consisted of cold engine started vehicles which had been parked there overnight. Vehicle emissions were considered representative of high altitude conditions.

The ventilation rate at the Los Angeles site was constant throughout the day; ventilation was turned off at night when there was little or no traffic. Exhaust vents were low level and the limited mechanical supply was ducted in or near ceiling height. This site was used for a variety of vehicle traffic including employees, fleet vehicles and public parking. The types of vehicles included both passenger vehicles and light-duty trucks. There was a peak traffic period in the morning, but traffic remained relatively constant throughout the remainder of the day. The Los Angeles site was considered representative of California vehicle emission conditions.

3.4 Air Quality Measurements

Non-dispersive infrared analyzers were used to monitor carbon monoxide concentrations for a week at each study site. Inert plastic sampling lines were run from a single analyzer to four fixed monitoring points at each site. Eight monitoring points (two analyzers) were used at the

Los Angeles site. All sampling lines were the same length to ensure that equivalent samples were obtained from each monitoring point regardless of its distance from the monitor. Air to be sampled was drawn through the lines continuously. Each line was sequentially analyzed for five minutes. Thus, each monitoring point was sampled every twenty minutes--or three times per hour. Averaging over time reduced the random variations and careful placement of monitoring points reduced potential systematic bias.

"Average CO" was calculated by obtaining an average CO concentration value for each monitoring point for each hour of the day and then combining the data from all parking level monitoring points into an overall average. The method avoided overemphasis of infrequent and randomly occurring "hot spots" arising from the coincidence of sampling points and individual vehicle movement.

The analyzers were calibrated twice per day using standard gas mixtures. The same standards were used for all calibrations at all study sites. The frequent intercalibration of instruments and uniformity of sampling and analysis procedures allowed direct comparisons of measured CO values between sites.

3.5 Vehicle Emission Measurements & Modeling

A computerized engine analyzer was used to measure vehicle emissions at each of the test sites. Emission values were compared to "predicted" emission values obtained from the EPA Mobil 1 Emission Factor Model (1978). The following assumptions were used in the development of the model:

Pollutant: CO
Average Vehicle Speed: 5 mph (8km/h)
Summer Ambient Temperature: 75°F (24°C)
Winter Ambient Temperature: 20°F (-7°C)
Traffic Mix: 88% light-duty vehicles, 12% light-duty trucks
Inspection and Maintenance Program: starting in 1981
Modes of Operation:
(1) 100% of vehicles operating in cold start mode
(2) 100% of vehicles operating in stabilized mode
Operating Regions: low altitude, high altitude, California
Years Estimated: 1980 and 1985

Emission factors from the model in grams/minute of CO were obtained by multiplying the grams/kilometer output of the model by the assumed vehicle speed of eight kilometers per hour and then dividing by sixty. The model also calculates hot idle emissions using the same assumptions. The model thus allowed calculation of:

1. Predicted CO emissions for 1980 and 1985 for both hot (stabilized) and cold start emissions.

2. Comparisons between predicted and actual hot idle CO emissions for both winter and summer conditions.

It should be noted that the number of individual vehicles actually tested was relatively small. For any future planning purposes, the "predicted" values are more likely to be appropriate (except for high altitude conditions: See Section 4.2.2).

3.6 Traffic Flow Measurements

Traffic flow patterns were monitored at each site with electromechanical traffic recorders. Car counts were stored and subsequently printed every twenty minutes. Entering and exiting cars at each site were counted and recorded separately.

In addition to entering and exiting traffic count, data were obtained on the average time each vehicle had its engine running in the garage. Vehicles were selected at random, followed and timed by observers with stop watches.

3.7 Ventilation System Measurement

Each supply and exhaust vent at all the sites was measured using a vane anemometer. Linear flow per minute was recorded and multiplied by the free air areas of the vent to obtain a volume flow rate. The free air area was assumed to be 0.7 of the total area of those vents with standard grill work.

For purposes of calculation, it was assumed that the total air flow in a given garage was equal to the larger of the mechanical supply or exhaust measurements, since excess air flow would be balanced by non-mechanical infiltration or exfiltration.

4.0 SITE RESULTS

4.1 Ventilation System

The effectiveness of currently applied ventilation principles for reducing CO concentrations in enclosed parking garages was studied in seven settings at the three geographic locations. The fundamental design principles used in each system differed sharply. The Los Angeles site design suffers from several problems:

1. Mechanical supply air in only one small area of the floor.
2. Reliance upon non-mechanical air infiltration to supply fresh air to a very large portion of the floor area, including a confined space far from any outside openings.
3. Single height exhaust vents.
4. Full "on" or "off" operation only.

The Hartford A&B design has both good and bad design elements:

1. Closely spaced supply and exhaust vents in positions which can be blocked by parked vehicles.
2. Structural impediments to free air flow.
3. Building wake coupling of outside air intake and exhaust structures.
4. Interior vents at two heights.
5. Two rates of ventilation scheduled to match traffic flow.

The Denver A&B design has:

1. No significant obstructions to free air movement.
2. Central supply vents that direct large volumes of air to the periphery of the floor where the air is mechanically exhausted.
3. No ventilation scheduling.

A summary of the ventilation data for the three sites is presented in Table 1. By comparing actual ventilation rates to the general ventilation design criteria, it is clear that only the Denver A&B designs meet both of the standard criteria. However, all sites meet the four to six air changes per hour guideline.

4.2 CO Concentrations

4.2.1 General Discussion. CO concentrations in underground parking garages are a function of:

1. Pollutant emission rate
2. Ventilation rate, schedule and efficiency
3. Vehicle use and traffic patterns
4. Outdoor ambient pollutant concentrations.

A primary objective of this study was to determine whether or not present design criteria are adequate to maintain carbon monoxide concentrations in underground parking garages within applicable standards, such as OSHA's standard of 50 ppm based on an 8-hr time-weighted average. Although two of the three study sites did not completely meet the ventilation volume per unit area design criteria, all sites met the 50 ppm/8-hr CO standard.

Present design criteria apparently provide adequate safety margins to maintain CO concentrations at acceptable levels for the sites studied.

4.2.2 Vehicle Emission Measurement and Modeling. CO emissions from vehicles were studied at the three sites to see if the emissions generally fell within the range of published data and to generally describe the nature of the emissions at each site. Table 2 presents predicted CO emissions from vehicles using the EPA Mobil 1 Model as discussed in Section 3.5. Seasonal and elevation differences are listed for cold and hot emissions for 1980 and 1985. Table 3 compares model-predicted hot CO emissions for 1980 and 1985 to actual hot emissions measured at the study sites. (Cold idle emissions were found to vary so rapidly with time that accurate measurements were not possible.) Vehicle emissions at the Hartford and Los Angeles sites were below the predicted values of 1980, and vehicle emissions at the Denver site were higher than the predicted values by almost a factor of two.

4.2.3 Air Quality and Traffic Measurements. Fig. 2 through 8 separately plot CO concentration, ventilation rate, and car count vs. time for each study site and floor level. Ventilation rates are displayed to illustrate fan schedules. The car count in a garage integrates all incoming and outgoing traffic for the particular hour in question over the week of the study. CO measurements were likewise integrated in order to reduce the impact of individual gradients in the garage as vehicle emissions coincident with sampling point activation.

Table 4 presents the average number of seconds a given vehicle was in operation while entering, exiting, or passing through a given garage setting. In addition to the effects of ventilation and car count on CO concentrations, summer/winter variations are apparent for the Hartford site. By coupling the use pattern data discussed in Section 3.3 with the car count data of the figures, the effect of cold start and hot (stabilized) emissions on CO concentrations are illustrated.

The worst-case design condition emerging from the data is a winter, cold-start, high altitude garage application. The condition coincides with a peak traffic period that may be in the afternoon for normal commuter traffic, or in the morning if the garage houses fleet vehicles that are parked overnight.

The effect of floor geometry and mechanical supply air (or lack of it) on CO concentrations can be seen by reviewing the results within three floor areas at the Los Angeles site. One area is serviced by mechanical supply air (monitoring points 5,7), one area is served by natural ventilation due to infiltration at the entrance ramp (monitoring point 3), and a third area is a confined space that is remote from both mechanical and natural ventilation (monitoring points 1, 2, 4). Table 5 presents data collected in each area. As might be expected, areas served by mechanical supply air had the lowest CO concentrations and the areas with no direct supply air, either natural or mechanical, had the highest CO concentrations.

4.2.4 Energy Conservation Potential. Since both the Hartford A and B and the Los Angeles sites already employed some form of fan operation scheduling, the potential for additional energy savings by scheduling alone is reduced. The Denver A and B sites, however, could benefit from a program which scheduled maximum fan operation to coincide with periods of garage use. The air change rate at full ventilation capacity is such that once traffic in the garage ceases, the indoor CO concentration quickly becomes equivalent to the outdoor ambient concentration and no particular benefit is achieved by further air transfer.

Maintaining a minimum air flow (approximately 25 to 50%) in the garage during off-hours would provide an appropriate safety factor for both unexpected traffic and static emissions such as gasoline fumes, yet could save appreciable operating expense.

5.0 DISCUSSION OF RESULTS

5.1 Ventilation Systems

5.1.1 General Discussion. Mechanical ventilation systems can be classified as supply-only, exhaust- only or combined systems. "Supply-only" refers to a system in which only supply air is provided by mechanical (fans and ducts) means. An "exhaust-only" system relies on passive routes of supply for its effectiveness. Combined supply and exhaust systems provide mechanical enhancement and control of both the supply and exhaust functions.

Most parking garages depend on combined or exhaust-only systems for ventilation. Exhaust-only systems would be likely to draw air from infiltration routes (stairwells, elevator shafts, plumbing and wiring spaces) rather than push contaminated air into other parts of the structure.

A combined system allows the designer more control of the distribution of clean air and, by adjusting or balancing the system, can prevent uncontrolled migration of polluted air to other parts of the structure.

Ventilation systems can also be classified as unidirectional or multidirectional. In a unidirectional system, the supply and exhaust points are arranged so that an overall flow field is established through a significant portion of the garage. A multidirectional system has supply and exhaust points interspersed so many small flow fields are established over relatively short distances. Supply-only, exhaust-only and combined ventilation systems can be either uni- or multidirectional.

The advantages of unidirectional systems include an efficient sweeping action which moves the pollutants quickly to the exhaust vents. A serious drawback of unidirectional systems in large structures is that high pollutant gradients can be established. The supply air is contaminated sequentially and additively as it travels toward the exhaust vent. By the time it arrives near the vent, it may have acquired a high pollutant loading and the area near the exhaust vents may not meet air quality standards. High total air flows and low leakage or infiltration from other areas are necessary for effective ventilation.

Multidirectional systems provide sources of clean air for pollutant dilution in a distributed manner and keep the overall concentration low. However, such systems increase the risk of "short circuits" in the ventilation flow. If the supply and exhaust points are too closely coupled, air can travel from one to the other without mixing with pollutant laden air outside the immediate transport path. A significant amount of the air being moved may have only a low pollution loading and the air not being moved may acquire dangerous concentrations of pollutants.

Short circuit flow can occur in a variety of ways. If supply and exhaust vents are too close to each other, or the flow is directed away from the intended path by obstructions such as parked vehicles, the flow from the supply can be channeled directly to the exhaust.

Internal short circuit ventilation does not always decrease system efficiency. It is theoretically possible to arrange short transport paths through the regions of highest pollutant emission and therefore remove the pollutants before they have had time to mix throughout the volume of the garage. There is a danger that too much reliance on localized systems can lead to inefficient removal of pollutants once they are out of the primary ventilation zone. Adequate flow must be maintained in all parts of the garage. In addition to short circuit flow inside the garage, "external" short circuit can occur when intake and exhaust structures on the exterior of the garage are coupled by adverse winds or building wake effects. Polluted air which has just been removed from the garage can contaminate the incoming supply air. This latter possibility, although an obvious design error, is often overlooked due to architectural constraints or unexpected wind effects.

5.1.2 CO Concentration Prediction Model. The efficiency of ventilation systems can be addressed in two different contexts: mechanical efficiency and operational efficiency. Mechanical efficiency includes such factors as the design of ducts, fans and vents. It deals with how much air in a structure is moved for a given expenditure of energy. Operational efficiency is more concerned with how well the system as a whole utilizes a given level of air movement to provide desired air quality. Since the chief concern of this study is air quality, this discussion will deal with operational efficiency.

The two factors which most strongly affect system operational efficiency are schedule and geometry. If the system is moving air out of a garage which is already clear of pollutants, the schedule is highly inefficient. Similarly, if air is being moved through the ventilation system, but some garage areas remain stagnant, the geometry is highly inefficient. Finally, if the air drawn in to replace the contaminated air in a garage is itself contaminated through recirculation or improper intake placement, the external vent geometry is inefficient and overall system efficiency will suffer.

To quantify system operational efficiency, the time-weighted average air quality which results from a given air volume flow can be compared with the value predicted by a model or "ideal" system. Such a model system would have the following characteristics:

1. All air exchange is due to the mechanical ventilation system.

2. Pollutants of concern are nonreactive; that is, their concentration after emission changes only through dilution and is not reduced by any physical or chemical reactions inside the garage.

3. Emission and mixing of pollutants and air inside the garage are complete and instantaneous with respect to the ventilation time scale.

For most underground parking garages, the above characteristics are reasonable assumptions. Air exchange by means other than the mechanical ventilation system is small. Some natural convection or pumping of air by moving vehicles is possible, but is small compared to the volumes of air moved by typical ventilation systems.

The pollutants of chief concern, such as CO and odorous emissions such as partially oxidized hydrocarbons, are essentially nonreactive compared to their residence time in a typical garage.

The major deviation from ideal behavior is related to non-ideal mixing. Mixing of air in the garage is enhanced by both the action of the ventilation system and by the turbulence related to the emission velocity and vehicle wake as vehicles move about the parking area. Mixing is suppressed by strong vertical temperature gradients, obstacles to free air flow and short circuiting of ventilation flows.

As discussed above, short circuits in a ventilation system could act to increase as well as decrease system efficiency. However, efficiencies much above 100% can be "unstable" since they often result in some areas of the garage receiving little ventilation relative to the prime emission hot spots. If a shift in traffic pattern changes the position of the hot spot, the overall ventilation may prove inadequate. Systems which promote good mixing are more resilient to small changes in emission pattern. It is generally easier to consistently achieve the mixing of gases than to consistently maintain their separation.

The garage sites studied in this program were compared in terms of operational efficiency. The results reported in Section 4.2 were used to provide the basic input needed for both modeling and comparisons. To implement the model calculations, it is necessary to know the ventilation rate, the pollutant generation rate and the volume of the garage. Of these, the greatest uncertainty generally concerns the pollutant generation rate.

The rate of pollutant generation depends on the number of vehicles in operation in the garage and the emission rate of each vehicle. All these factors are highly variable. By using average values derived from many days of observations, much of this variation will be smoothed out. Averaging over time periods of at least one hour is necessary to validate the assumption of complete and "instantaneous" mixing and is convenient for assessing the possible effects of system scheduling. The one-hour averaging time is also the maximum for which the rate of total vehicle emissions can be considered constant.

The model for the ideal system used in this study considered the pollutants generated within a one-hour period as dispersed into a box with a volume equal to the volume of air moved by the ventilation system. A correction is applied for the original volume of the garage and any concentration of pollutant present initially inside the garage or in the supply air. Such a "box model" is unlike an exponential dilution model in that it is based on an assumption of continuous and uniform generation of pollutants inside the garage, rather than dilution of an initial concentration.

Working on this basis, the calculation of concentration becomes:

$$C = \frac{E + C_o V_o + C_A V}{V + V_o}$$

where: C = concentration of pollutant

E = pollutant emission during one hour

C_o = initial concentration of pollutant inside the garage at the start of the hour

C_A = outdoor ambient pollutant concentration at the supply air intake

V_o = volume of the garage

V = ventilation volume during one hour.

Predicted CO concentrations can be compared to actual concentrations and the degree of comparison will indicate how well the assumptions made in the model apply to the real garage. A "Ventilation System Ideality" (VSI) factor can be defined:

$$VSI = \frac{CO\ (predicted)}{CO\ (actual)}$$

When VSI = 1.0, it implies the actual system behaves in the same way as the "ideal" or model system. A VSI value greater than or less than 1.0 implies that the system is non-ideal in one or more ways. It is possible that a VSI = 1.0 could result from two offsetting deviations from ideal behavior, but the likelihood that such errors would cancel consistently for different conditions is low.

Two major components of non-ideal behavior are:

1. differences in emission rate of vehicles using the garage from average emissions, and

2. non-perfect mixing of pollutants with the air inside the garage.

The first factor can be especially significant when the number of sources inside the garage is small. The probability of any individual vehicle emitting at exactly the average rate for its type is low. Thus, the fewer vehicles that operate, the greater the likelihood that actual emission rates will significantly differ from expected values used in the model. This potential source of difference is effectively random and is reduced by averaging measurements over several days.

A more interesting source of "error" or difference between predicted and actual CO concentrations rests on the assumptions of perfect mixing used in the model. As discussed above, short circuits in the ventilation flow can either increase or decrease effective ventilation efficiency. VSI values significantly greater than 1.0 indicate the system has a high degree of efficiency, but is potentially unstable with regard to providing consistently good air quality. Similarly, VSI values significantly less than 1.0 imply the system is moving more air than necessary to remove a given pollutant load.

Fig. 9 and 10 illustrate VSI factors for the Denver B and Los Angeles sites, respectively. As can be seen in the figures, the two sites have distinctly different patterns of VSI factors as a function of time. At site Denver B, the VSI factor is consistently less than 1.0, indicating that predicted CO concentrations are lower than actual values for most of the day. The difference can be explained by the difference between the vehicle CO emission rates predicted from EPA calculations and the measured CO emission rates. The discrepancy highlights the importance of emission variability among the vehicles actually using the garage and the need for adequate safety margins. However, as seen in Fig. 5, the actual CO concentrations are still far below the allowable limit and adequate air quality could be maintained with much lower total air flow.

In Los Angeles, the VSI factor clearly reflects the impact of the mechanical ventilation system. When the mechanical exhaust system is operating, the predicted and actual CO concentrations are nearly equal, and the VSI factor is close to 1.0.

During periods when the mechanical system is off, the model predicts much higher values than actually occur. Such a result is not unexpected, since one of the basic assumptions was that ventilation flow is equal to zero with the mechanical system off. Thus, even limited nonmechanical ventilation can help reduce CO levels. However, it should be noted that traffic is light and CO levels are relatively high in this particular garage during "off" periods.

The VSI factors for Hartford data are not calculated due to gaps in the record for ambient outdoor CO concentration.

The major conclusions which can be drawn from the limited analysis of VSI factors performed is that relatively good agreement (within a factor of two) between actual and predicted CO concentrations is possible using the model presented. In order to use the concepts discussed here to plan an optional ventilation strategy, it is necessary to consider:

1. the level of contamination considered acceptable inside of the garage;

2. the minimum safety margin desired;

3. the traffic pattern or schedule; and

4. the efficiency of the ventilation system as operating.

For example, if an existing garage has a traffic flow far greater during certain predictable periods than for others, the appropriate ventilation rate for those hours can be calculated from the box model described above and the measured ventilation system ideality (VSI) factor. It is recommended that VSI values greater than 1.0 not be considered unless an exceptionally large safety margin is already used. VSI factors are based on the results of study at the three field sites only. More extensive data gathering is necessary before the model can be presented in more definitive terms.

5.2 Design Criteria

Present design criteria vary from one code to another and the design relationships between CO concentrations, ventilation rates and layouts, and building design are not completely described.

Basic design criteria that are most frequently encountered are:

1. Air changes per hour: 4-6, ASHRAE 1977 Fundamentals Handbook

2. Ventilation rate
   7.5 $l/s/m^2$ (1.5 cfm/ft^2) minimum; 10 to 15 $l/s/m^2$ (2 to 3 cfm/ft^2) recommended, ASHRAE 1977 Fundamentals Handbook

3. Number of cars in operation: 3-5% normal; 15-20% peak use.

4. Emission rates: EPA motor vehicle emission factors.

5. Length of car operation: 60 to 180 seconds.

6. CO concentration standard: 50 ppm, 8-h. (time-weighted average); 125 ppm 1-h. (Time-weighted average) (More stringent above 1067m or 3500 ft but no specific high altitude standard is stipulated by OSHA).

In addition to the above criteria, local building codes should also be checked and complied with. As stated earlier in Section 4.1, some of the above design criteria were not met at all of the sites studied, but the CO standard was met in all cases. Substances other than CO, such as oxides of nitrogen, smoke and soot, fuel vapors, particulate sulfates and odor causing compounds may be of concern from the standpoint of public acceptability. There is limited information available to the designer that describes the synergistic effects of such substances. To some extent the designer can use the "Appendix C, Mixtures" procedures that are outlined in Threshold Limit Values for Chemical Substances in Workroom Air, American Conference of Governmental Industrial Hygienists (updated annually).

In addition to synergistic effects of multiple substances, design allowances must also be considered for winter/summer, fan schedule and altitude variations. The results reported in Section 4.2 clearly illustrate that a garage that marginally complies with the standards in the summer may violate standards in the winter, particularly for high altitude applications. Further study is necessary to define the design criteria that will accommodate the numerous contributors to varying pollutant concentrations.

Multiple substances, seasonal and altitude considerations are not presently included in design criteria. It can be concluded, however, that the present design criteria are adequate to meet the CO concentration standard at the sites studied with the operating and car use conditions that prevailed at the time of the study.

APPENDIX

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Table 1. Summary of Ventilation Data

SITE	AUTOMOBILE CAPACITY	MECHANICAL EXHAUST RATE ℓ/sec.	MECHANICAL SUPPLY RATE ℓ/sec.	GARAGE VOLUME m^3	AIR CHANGES PER HOUR	VENTILATION RATE PER FLOOR AREA $\ell/s/m^2$
Hartford A	270	18780 (2780 off-hrs)	32800 (2780 off-hrs)	22560	5.2 (0.4 off-hrs)	3.5 (0.3 off-hrs)
Hartford B	270	18830 (3260 off-hrs)	45680	21150	7.8 (0.6 off-hrs)	5.1 (0.35 off-hrs)
Denver A	203	16280	19400	4430	15.8	10.2
Denver B	170	8825	13100	2820	16.7	10.7
Los Angeles	264	21945	12750	18730	4.2	3.5

ASHRAE VENTILATION DESIGN CRITERIA

1. 7.5 $\ell/s/m^2$ (1.5 cfm/ft^2) minimum; 10 to 15 $\ell/s/m^2$ (2 to 3 cfm/ft^2) recommended. (ASHRAE 1977 Fundamentals Handbook)

2. 4 to 6 Air Changes Per Hour. (ASHRAE 1978 Applications Handbook)

Table 2. Model-Predicted Co-Emissions[1]

Location	Hot Emissions (Stabilized) gm/min 1980	1985	Cold Emissions gm/min 1980	1985
Sea Level				
Summer	12.3	3.6	25.0	9.4
Winter	12.3	3.6	59.4	20.1
High Altitude				
Summer	13.3	3.9	34.3	11.5
Winter	13.3	3.9	83.1	24.7
California				
Summer	9.3	2.6	22.9	9.7
Winter	9.3	2.6	42.1	16.1

[1]Results from EPA Mobil 1 model, (8 km/h assumed vehicle speed)

Table 3. Predicted and Actual Hot Idle Emissions

Location	Predicted CO[1] Emissions (gm/min) 1980	1985	Actual CO Emissions (gm/min)
Hartford			
Summer	19.5	9.1	11.3
Winter	19.5	9.1	9.2
Denver			
Summer	16.7	8.6	32.7
Winter	16.7	8.6	-
California			
Summer	15.9	4.7	12.8
Winter	15.9	4.7	-

[1]Obtained from EPA Mobil 1 model.

Table 4. Average Entrance, Exit and Pass-Through Times For Site Vechicles

LOCATION	AVERAGE ENTRANCE TIME, sec.	AVERAGE EXIT Time, sec.	AVERAGE PASS-THROUGH Time, sec.
Hartford			
Level 1 (A)	34	48	-
Level 5 (B)	67	95	-
Denver			
Level B-3 (A)	40	49	30
Level B-4 (B)	43	72	-
Los Angeles	64	50	57*

*Represents valet parking time.

Table 5 Los Angeles, Local CO Concentrations

	AVERAGE CO CONCENTRATION, PPM					
	MECHANICAL SUPPLY AIR	NATURAL SUPPLY AIR		NO SUPPLY AIR		
TIME PERIOD	MONITOR #5	MONITOR #7	MONITOR #3'	MONITOR #1	MONITOR #2	MONITOR #4
0800 - 0900	16	10	20	25	25	23
0900 - 1000	13	7	20	30	25	21
0800 - 1100	14	8	19	29	26	22

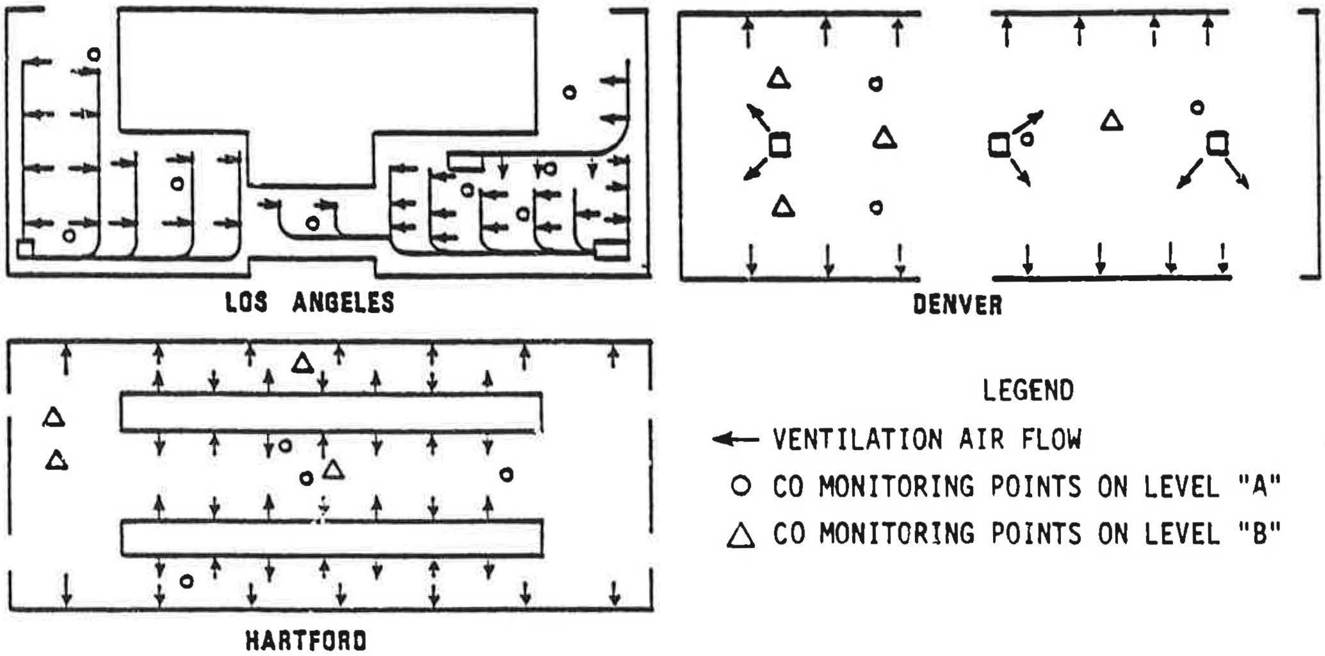

Fig. 1 Schematic design - parking garage geometry

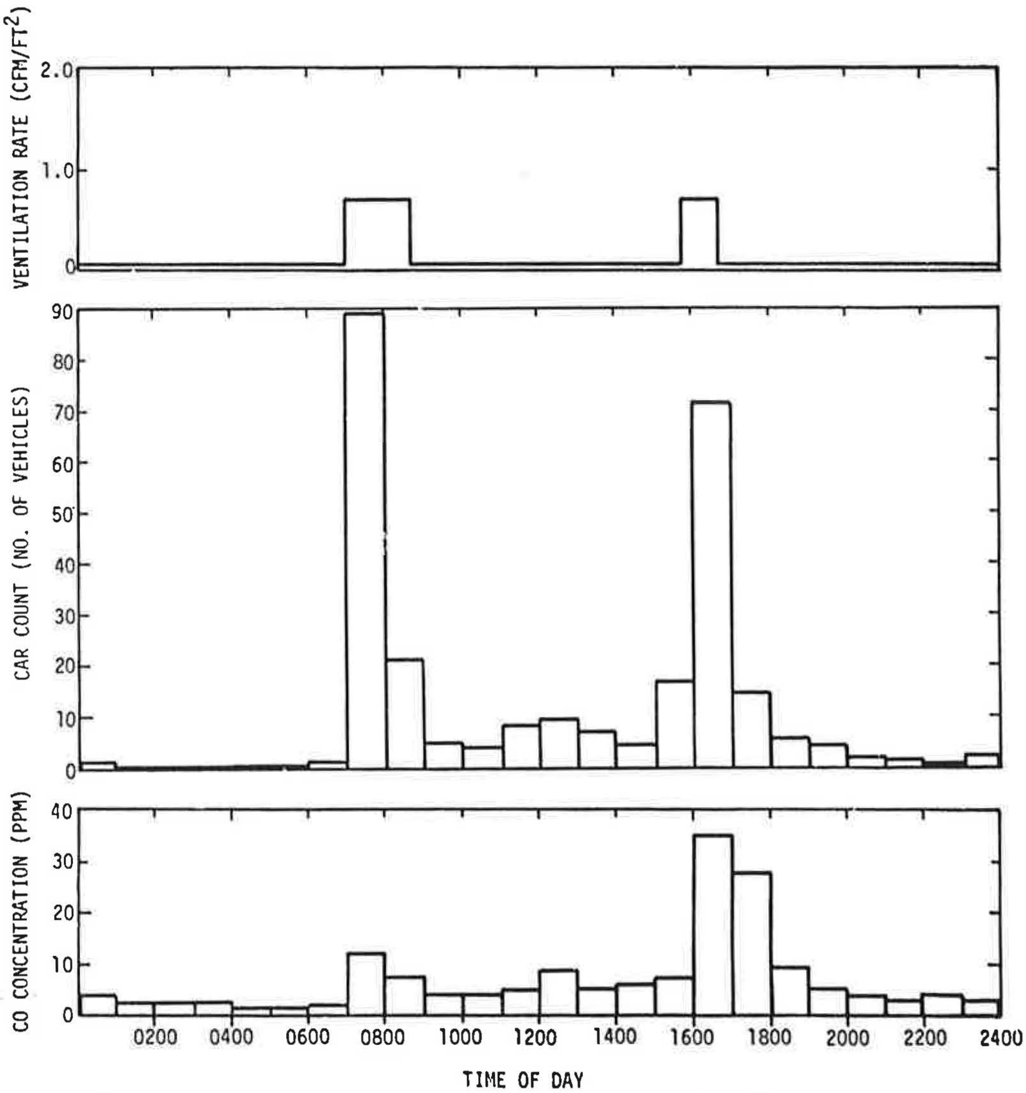

Fig. 2 Site No. 1, summer, Hartford A, CO concentration, car count and ventilation rate vs time

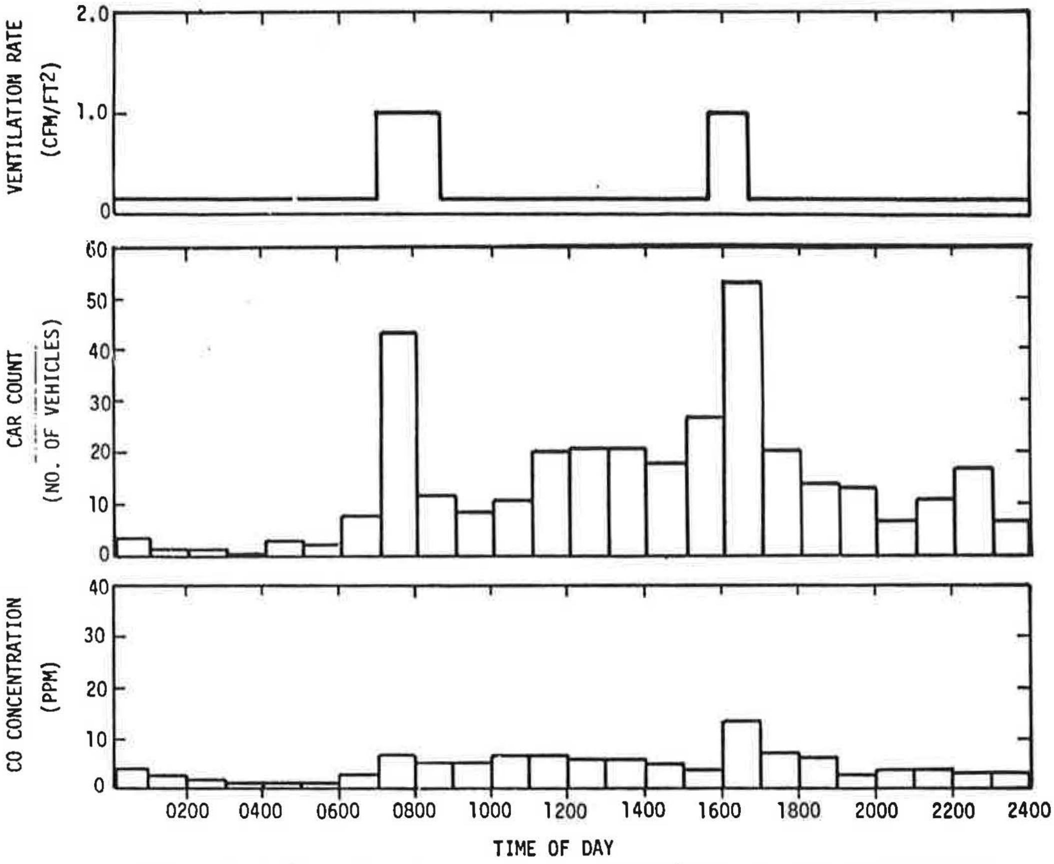

Fig. 3 Site No. 1, summer, Hartford B, CO concentration car count and ventilation rate vs time

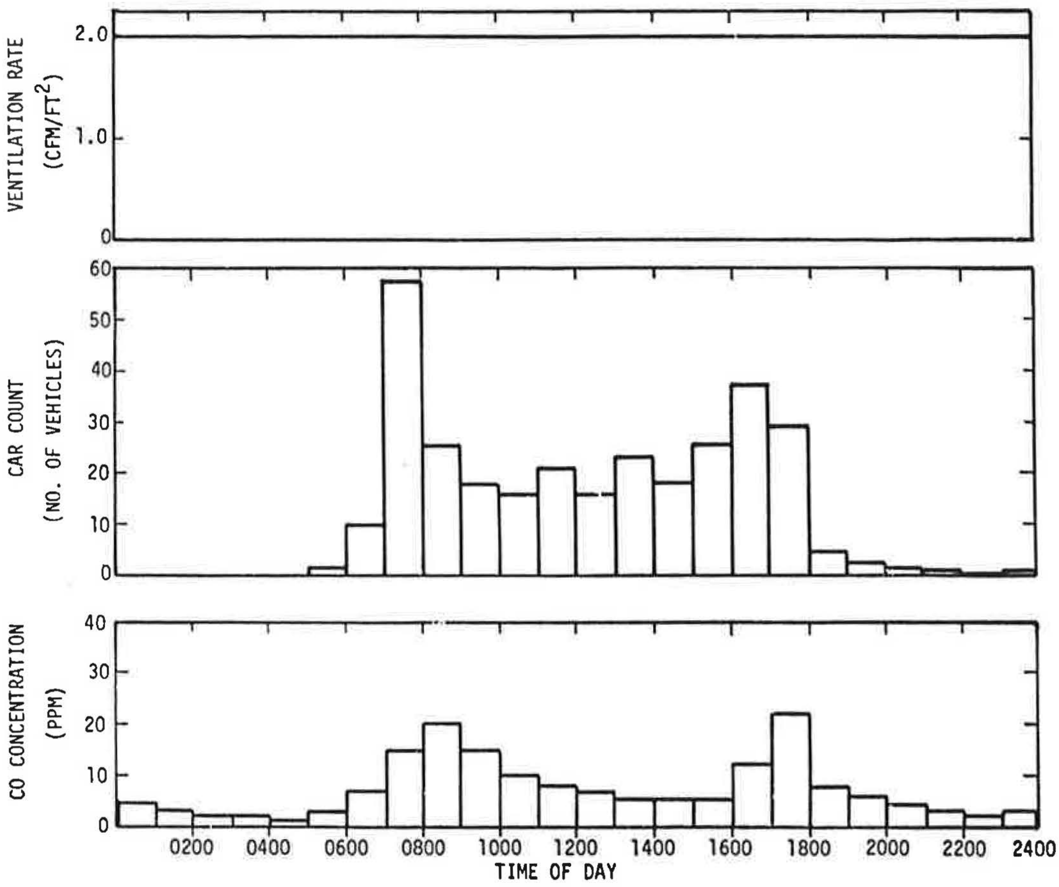

Fig. 4 Site No. 2, Denver A, CO concentration, car count and ventilation rate vs time

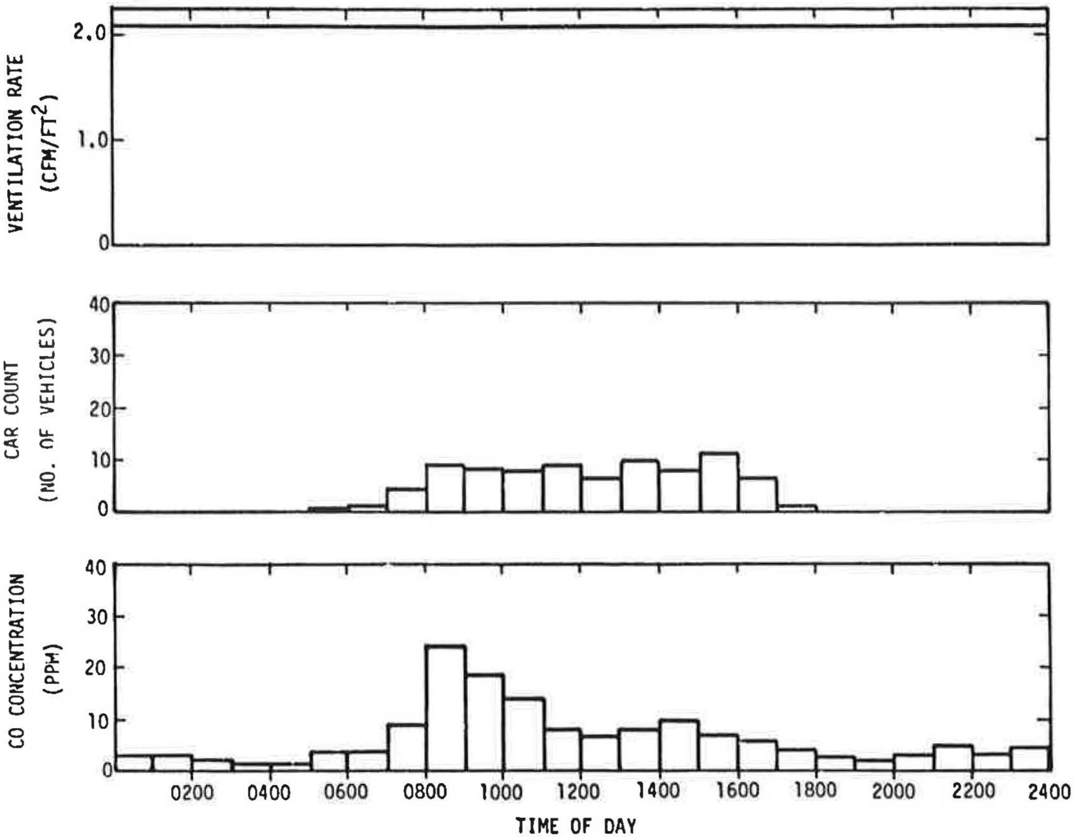

Fig. 5 Site No. 2, Denver B, CO concentration, car count and ventilation rate vs time

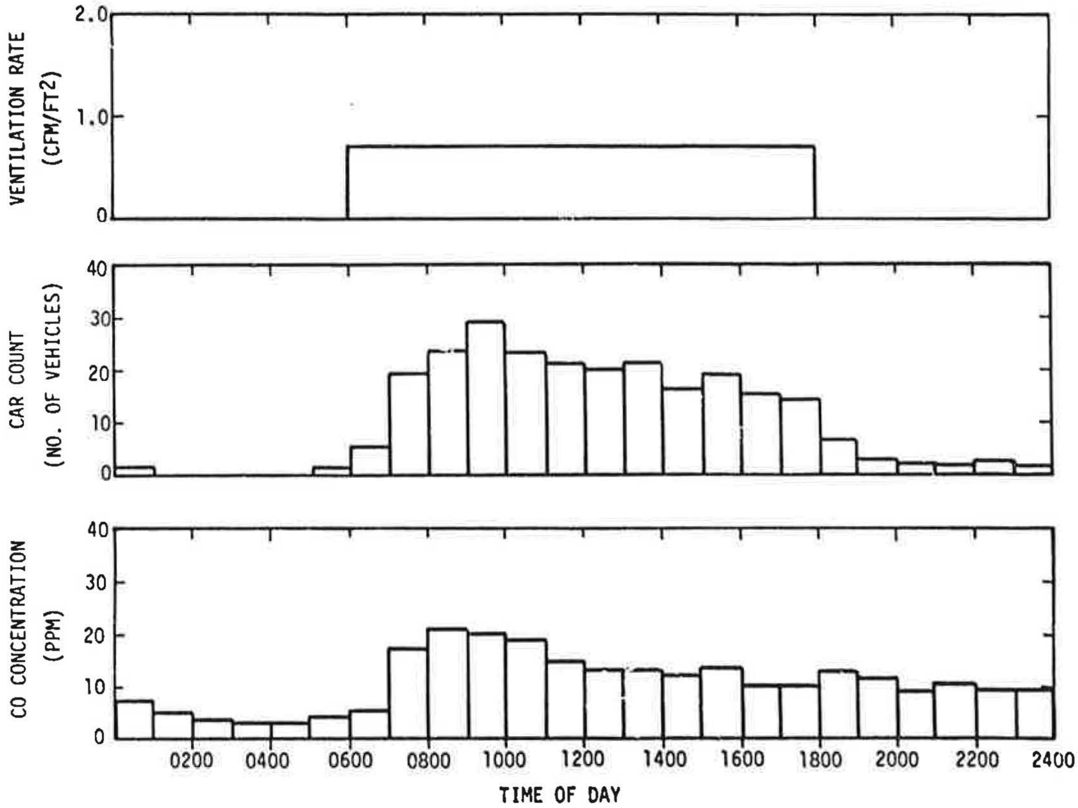

Fig. 6 Site No. 3, Los Angeles, CO concentration, car count and ventilation rate vs time

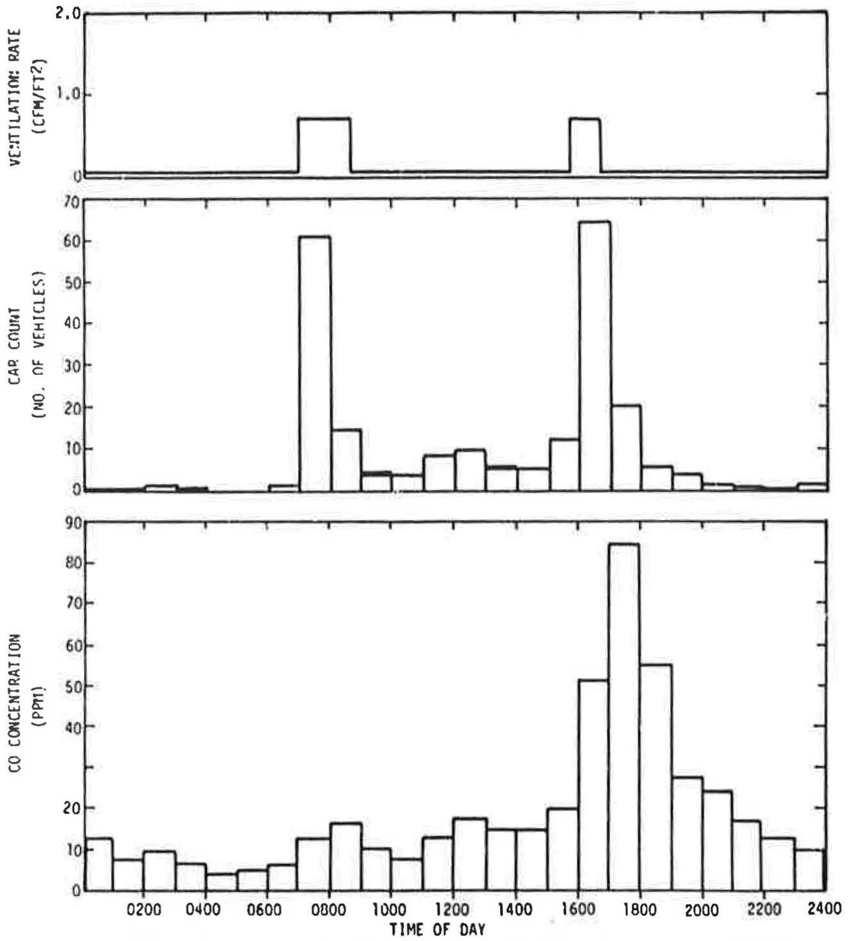

Fig. 7 Site No. 1, winter, Hartford A, CO concentration, car count and ventilation rate vs time

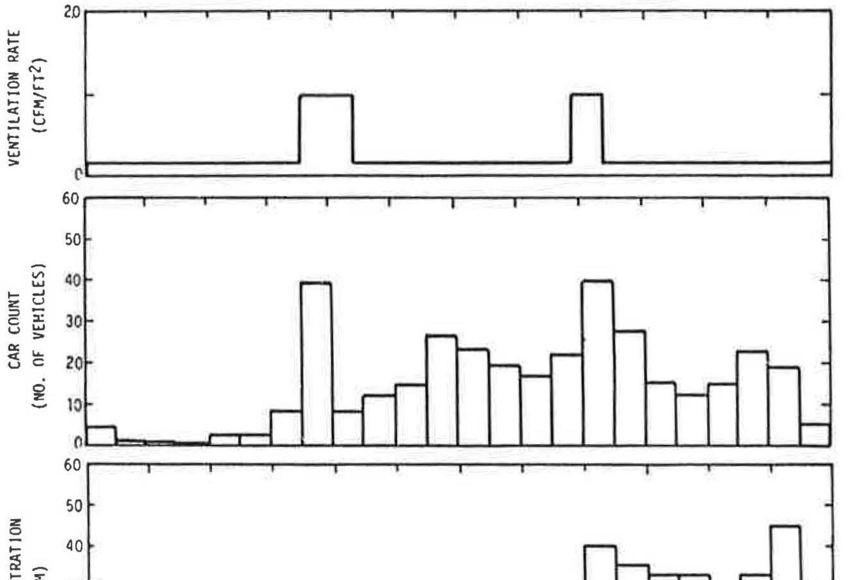

Fig. 8 Site No. 1, winter, Hartford B, CO concentration, car count and ventilation rate vs time

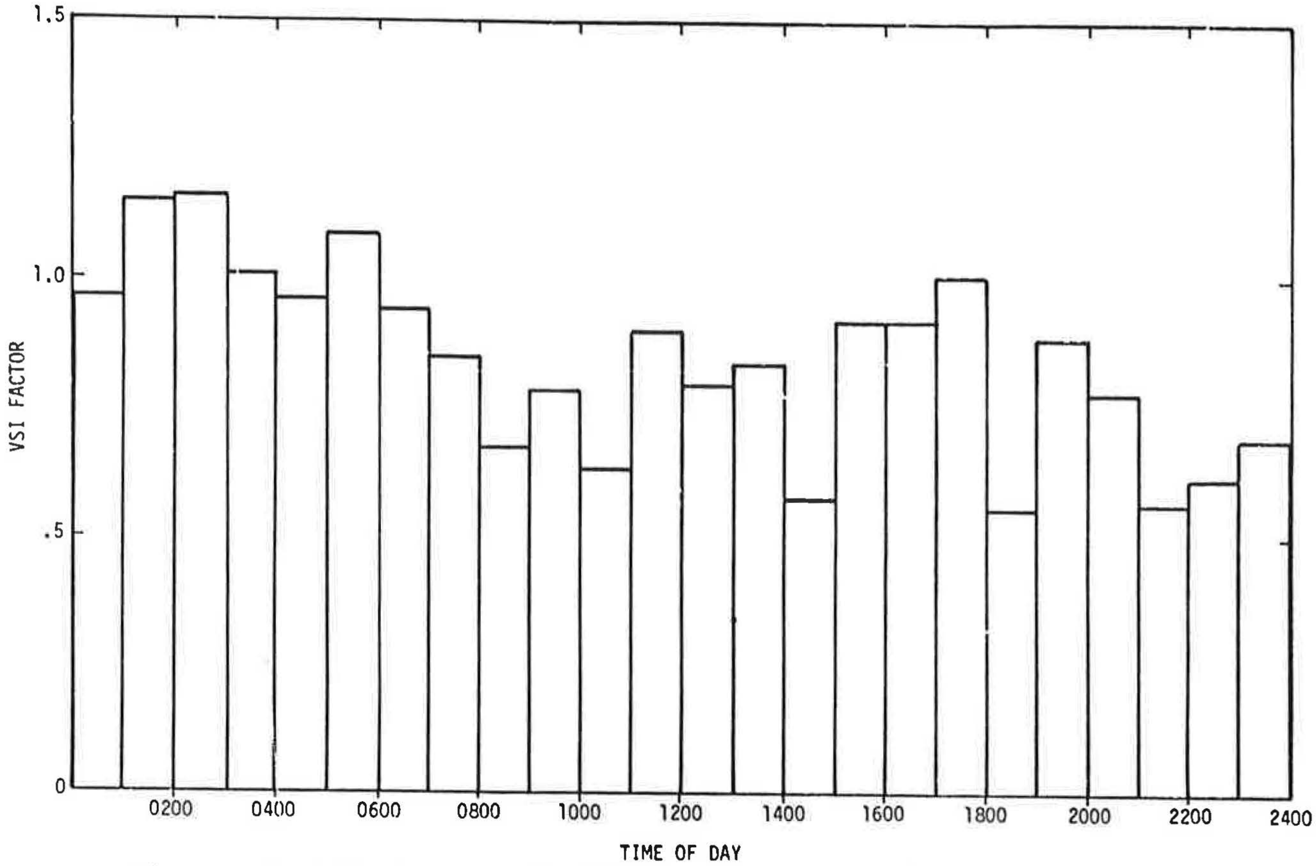

Fig. 9 Ventilation system ideality factor vs time for Denver B

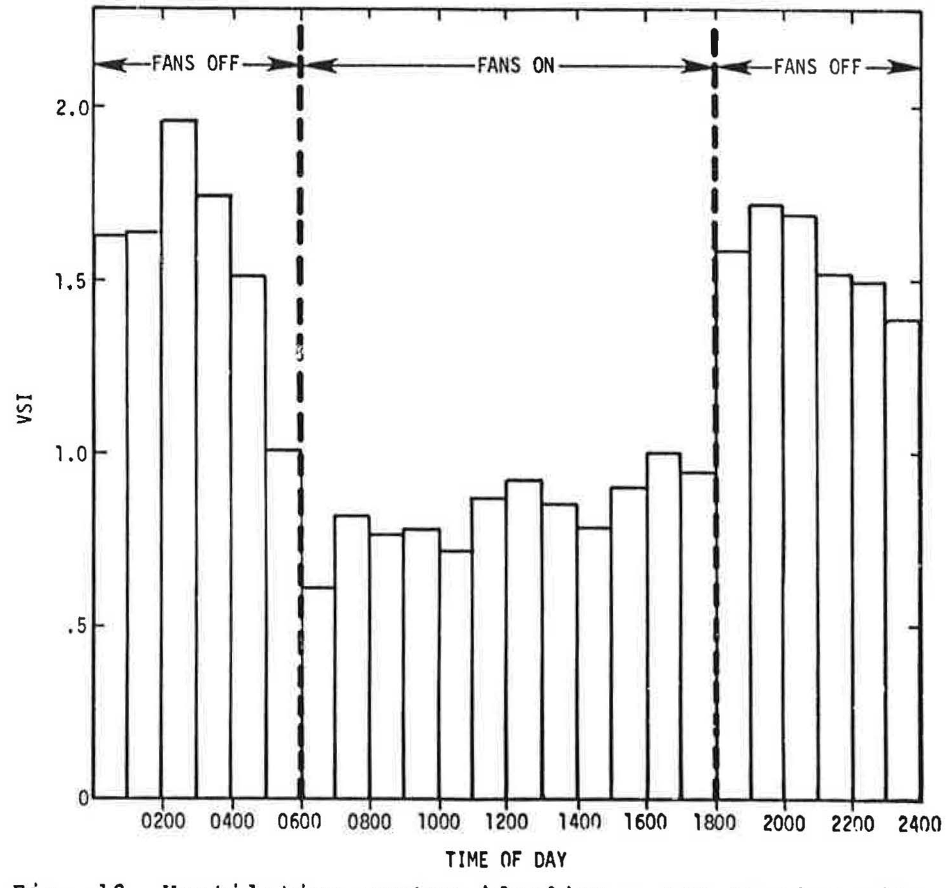

Fig. 10 Ventilation system ideality - Los Angeles site

DISCUSSION

RICHARD A. CHARLES, Mech. Engr., Charles & Braun, San Francisco, CA: Have you seen CO monitoring systems used to control fan usage?

ALEXANDER R. STANKUNAS: No, I did not observe CO monitoring systems controlling fan usage in any of the parking garages we investigated. However, I have seen systems where continous CO monitoring is used as part of a warning system. If CO levels exceed certain threshold levels, warning signals and signs are activated to curtail vehicle operation in the garage. At the particular garage where I saw this system, it has never been necessary to test how well motorists would comply with the warnings.

HUGO S. MILLER, M.E., Merle Strum & Assoc., San Diego, CA: In your study, did you evaluate high or low exhaust pick-up, temperature or other types of control of exhaust fans in relation to CO or odor removal?

STANKUNAS: We were not able to quantitatively investigate the influence of all the factors we would have liked. Since each site presented a unique combination of factors, it was not possible to vary some and hold all others constant without greatly exceeding practical limits on the number of sites we could study.

We did investigate temperature gradients as a possible indicator of exhaust buildup, but found that the turbulence of passing vehicles disturbed such measurements to the extent that they could not be used reliably.

The height of exhaust pickup varied in the garages studied, and we recommended use of bi-level vents. Such a system ensures that rising hot exhaust gases are vented as well as any cool, dense fuel vapor emissions.

GILBERT A. BONFORTE, Chief Tunnel Engr., TAMS, New York, NY: Should not the ventilation system design take into account the "worst condition" situation--similar to what is done in tunnel design (e.g., the tunnel filled with cars, all engines at idle)? The Hartford garage is a case in point.*

STANKUNAS: Design for "worst-condition" situations is different than standard operations for such situations. Having a fan capacity capable of handling peak loads, but only using that capacity as necessary, can result in significant energy savings. As for the Hartford garage example, the high CO levels only occur in winter afternoon rush-hour conditions. The point of our report was that fan operation during other periods can be significantly lower and still maintain adequate air quality.

BONFORTE: What are the ramifications of litigation against the owner?

STANKUNAS: Although, I am not a lawyer, I would imagine the potential for litigation against the garage owner or operator who uses a variable intensity ventilation system is similar to that for any garage owner/operator. He is responsible for providing adequate air quality and safety inside the garage. If the garage is not operated in an appropriate manner, he is liable, regardless of the type of ventilation system employed.

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*The afternoon peak load creates overly high CO levels for more than two hours.

D.F. OWENS, Cons., D.F. Owens Co., Bainbridge Island, WA: What were your observations of haze?

STANKUNAS: Haze was not a serious problem with regard to impaired visibility or safety. However, it could be significant in terms of the public's perception of air quality inside the garage and should thus be factored into the ventilation system design requirements.

DICK HEGBERG, P.E., L.E. Schulein Co., Melrose Park, IL: Your study covered only enclosed garage structures. Would you comment on the partially enclosed or grilled structure? When is ventilation required for the partially enclosed structures?

STANKUNAS: The ventilation requirements for partially enclosed structures are very difficult to assess in any general sense. The tremendous impact of wind and the aerodynamic influence of surrounding structures makes such analysis extremely complex. I have no advice or rules-of-thumb for mechanical ventilation requirements based on wall density or floor area that can be derived from our study since each situation is so different.