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colorado tunnel ventilation study

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16. Abstract

Mechanical ventilation of tunnels is costly because of the initial installation and the continued maintenance and operation. However, at some tunnel length corresponding to a particular altitude, traffic configuration and topography there is a need for this forced ventilation. This study was undertaken to help determine the pollution concentration in existing tunnels in Colorado, and predict the length of tunnels which will need mechanical ventilation.

The study indicated that, even a high altitudes, tunnels will vent very well when the length is less than 2000 feet and traffic is less than 1500 vph. Above these limits, combinations of increased length and increased traffic may require some type of mechanical ventilation for tunnels serving vehicles with internal combustion engines similar to those used today.

The greatest pollution concentration condition occurs when vehicles are stopped and engines continue to "idle." When vehicles are in motion the induced wind will be approximately 7 mph and contribute significantly to the dispersion of pollutants.

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SUMMARY

There is a very definite need to determine the safe maximum length of a tunnel carrying up to 2000 vehicles per hour without the use of mechanical ventilation. Approximately 15 tunnels are planned for construction on the Interstate system in the mountains of Colorado. Mechanical ventilation is costly for both construction and maintenance, so if some or all of these tunnels can be designed short enough, a saving of as much as $1,100 per foot of tunnel for a possible total of $21,000,000 could be realized.

In this study, previous findings of tunnel ventilation design were investigated, and the tunnels of various lengths being used by vehicle traffic above the 5000 foot elevation were investigated. Induced wind, concentrations of carbon monoxide, hydrocarbons, nitrogen oxides and particulates were measured. Old formulas for predicting pollutant concentration were checked and new formulas were devised. Pollutant emission rates of 40 representative vehicles operating at high altitudes were measured, and idle emission rates were determined. Effects of idling inside a 9000 foot long tunnel at the 11,000 foot altitude were studied by actual field test.

From an analysis of this data, it was determined that there is a very helpful induced wind developed when vehicles move at about 40 mph inside a tunnel. This airflow disperses the pollutants and will effectively carry them out to the ends of the tunnel if the tunnel is less than 2000 feet long.

If it is necessary for the tunnel to be longer than 2000 feet, the flow of traffic will have to be carefully regulated, and some means of mechancial ventilation probably should be provided for emergency means at least. Best efficiency can be obtained from fans at high altitude by the use of large ducts and openings directly into the tunnel. Numerous long, curved vent lines will seriously reduce airflow, increase the expense, and provide problems associated with moisture drainage and corrosion.

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INTRODUCTION

More tunnels are being planned for highways through mountainous or rolling terrain. Data is available for the design of these tunnels at sea level, but Department of Health officials have become concerned about the design of tunnels at high altitude because of the carbon monoxide emission of vehicles and the cardio-respiratory and anemic conditions of some persons. Certain smokers and people with sickle cell anemia are particularly susceptible to concentrations of carbon monoxide. This group may compose 25% of the motorists in Colorado. It is estimated that from 7% to 15% of American black persons are affected by sickle cell anemia. Carboxyhemoglobin concentrations in persons smoking 20 to 30 cigarettes daily range from 3% to 10%, and it is estimated to take 4 or 5 hours to bring the carboxyhemoglobin concentration down from 10% to 5% even if pure air is breathed.

Long tunnels used for motorized vehicular traffic are often provided with a power driven means of reducing the pollutant concentration. If the tunnel is long enough and if the traffic is heavy, that system of forced ventilation may be very costly. As an example, the ventilation system used at the 1.67 mile tunnel for Interstate 70 under the Continental Divide cost over $823 per linear foot which is an investment of over $9,000,000.

The purpose of this research is to determine the residual carbon monoxide, hydrocarbon, and oxides of nitrogen content in tunnels throughout the State of Colorado at different elevations, different traffic, wind and climatic conditions, and analyze the data with respect to safe limits. It is anticipated that from this data there will be some indication of what the ventilation requirements will be for different lengths of tunnels at high altitudes.

Approval for this Project was received from the Federal Highway Administration on February 24, 1971. Work began by ordering the necessary equipment and arranging for tunnel readings at that time.

PREVIOUS INVESTIGATIONS OF POLLUTANT CONCENTRATIONS

One of the best State of the Art Reports based on a Literature Search along this line is the one completed by the California Division of Highways' Bridge Department in 1969.(1)

Some of the facts brought to light in this report are the following:

1. Under normal conditions, a carbon monoxide concentration of 250 parts per million is a better figure to use as a maximum concentration in a tunnel than the 400 ppm formerly indicated by the Bureau of Mines.
2. Natural ventilation due to temperature and barometric differentials and piston effect are not reliable enough for the design of today's tunnels.
3. Tunnels up to 1,000 feet in length can safely be regarded as self-ventilating, but some means of mechanical ventilation should be provided in tunnels over 3,000 feet long. There are some exceptions to this rule. Vehicles going 45 mph, spaced 50 feet apart will normally build up the carbon monoxide concentration to 170 ppm in a 2,000' tunnel and to 250 ppm in a 3,000' unventilated tunnel.
4. One of the reasons for mechanically ventilating tunnels

over 1,000' long is to reduce haze. Tests made by the Bureau of Mines have shown that when there was enough smoke to absorb 70% of the light, visibility was sufficiently restricted to prohibit safe driving. Diesel vehicles are the main contributor to haze, but poorly adjusted, old, gasoline-powered vehicles will also emit smoke.

A computer output from the Highway Research Information Service supplied a number of other sources of information regarding the ventilation of tunnels. Apparently, considerable work has been done along this line - especially by the Japanese. However, most of the data is for elevations between sea level and 5,000 feet. Some of the significant findings are as follows:

1. A report by A. Haerter in the TECH CIRCUL ROUTIERE, ISCHIA ITALY(2) discusses ventilation systems in tunnels and quotes the carbon monoxide content of 100-150 ppm as the figure upon which calculations must be based. The Fort Pitt tunnels show daytime readings from 50 to 150 ppm except at peak periods when the concentration rises to 200 ppm or even 290 ppm if fan speeds are not increased in advance. The Baltimore Harbor Tunnel averages 75 ppm with peaks of approximately 180 ppm. MSA averaged 5 important tunnels in the United States and got 54 to 170 ppm.
2. Holtz and Dalzell(3) of the U. S. Bureau of Mines found that the build-up of nitrogen dioxide was only to a trace in studies of diesel engine operation in a 10,000' ventilated tunnel.

3. T. Mitani and R. Aisawa(4) working for the Japan Mechanized Construction Association concluded that under normal conditions, the limit of length of tunnels utilizing natural ventilation is 1,600 feet. On tunnels longer than 3,300 feet, artificial ventilation required is 75% of normal requirement because 25% will be supplied by the natural ventilation. The Armstrong Tunnel in Pittsburgh, Pennsylvania is 1,350' long and has no ventilating fans. It carries about 30 vehicles/min and shows an average CO concentration of 50 ppm.

4. The Mine Safety Appliance Corporation(5) has extensively investigated the field of tunnel ventilation under contract with the Federal Highway Administration. In addition to publishing an excellent review of the subject, they have assembled a computer model which will determine contaminant concentration at various points within a tunnel when certain information regarding traffic and emission rates are supplied. A check of this model with data from Colorado tunnels will constitute a considerable portion of this report on following pages.

5. The California Highway Division has undertaken a $400,000 project to develop mathematical models to represent diffusion of contaminants along open roadways. Envisioned is a mechanical mixing cell where there is an intense zone of mixing and turbulence caused by the motion of the vehicles. Although the concept was developed to calculate concentrations on an open

freeway, data from this Colorado high altitude study will be analyzed to some extent by means of the California model.

6. Model and full-scale systems have been used by Gurney and Butler[6] to measure the drafts induced by the movement of traffic in unventilated tunnels. An approximation theory has been used to predict the carbon monoxide contamination likely to be experienced under various conditions of traffic flow. Results show that for tunnels up to moderate lengths, the level of carbon monoxide contamination is likely to remain within safe limits except under the most odorous conditions of traffic operation, and that tunnels up to 1,000 feet in length can be regarded as self-ventilating, for all practical purposes. It was found in full-scale tests at the London Airport, however, that adverse winds could more than halve the vehicle-induced drafts, showing that the orientation of the tunnel and local topography must be taken into account.

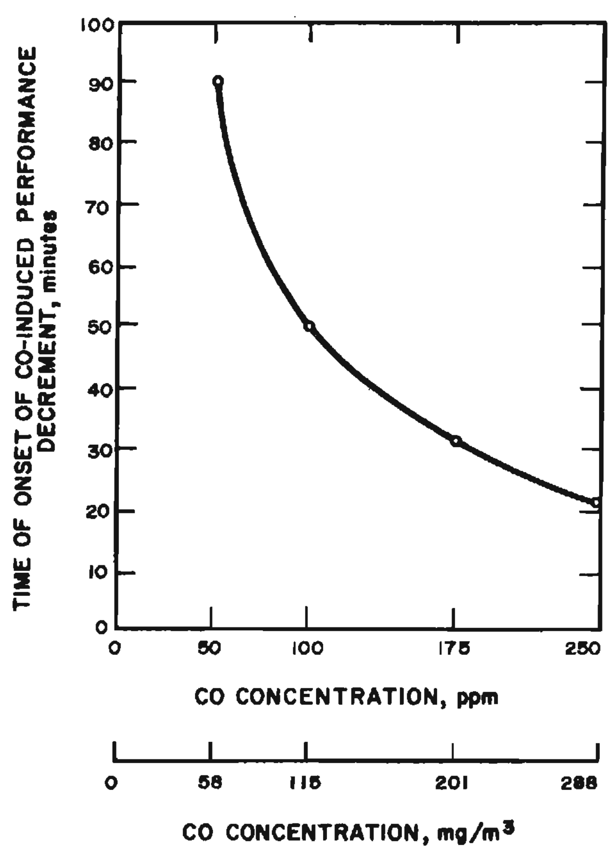
   The main variables considered likely to influence the induced flow are speed, spacing, shape and length of the vehicles; length, diameter surface roughness and entry and exit conditions of the tunnel; and pressure difference between the ends of the tunnel.

Along the line of Human Tolerance to carbon monoxide, significant findings are as follows:

1. R. R. Beard[7] of Stanford University reported that at a CO concentration of either 150 or 250 ppm, impairment of relative brightness discrimination was observed after only 17 minutes of exposure. At 50 ppm it took 49 minutes of exposure to bring about an impairment of relative brightness discrimination.

The time of onset of CO - induced auditory performance decrement according to the concentration of CO in the atmosphere is shown below:

FIGURE I



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2. The HEW report[8] entitled AIR QUALITY CRITERIA FOR CARBON MONOXIDE states that most experimental data suggests that when high altitude and CO exposures are combined, the effects are additive. By contrast, E. P. Vollmer[8] found that the effects of CO and altitude are not additive. Results of tests on humans do seem to agree, however, that combined exposure to CO at an altitude of 10,000 feet produce impairments that neither of these stresses alone will show.

3. The American Conference of Governmental Industrial Hygienist recommends a maximum CO level of 50 ppm for industrial workers during an 8 hour work period. However, it should be mentioned that very few tunnels are over 2 miles long, and at 40 mph, the average motorist would only take 40 or 50 breaths of contaminated air because the travel time inside the tunnel would only be 3 minutes or less. Pennsylvania Department of Health report on SHORT TERM LIMITS FOR EXPOSURE TO AIRBORNE CONTAMINANTS reveals that a concentration of 1,000 ppm of CO could exist for 10 minutes without creating unacceptable conditions for tunnel users. In view of these findings, the recommendations of 50 ppm maximum in tunnels seems highly restrictive.

4. Current emergency alert levels for air pollution episodes in effect for Metropolitan Denver Air Quality Control Region[9] are as follows:

Pollutants	Indicator Levels (5 Min. Peaks)	Standby Alert Levels (Max.hrly avg. conc)	Full Alert Levels (max.hrly avg. conc)
Carbon Monoxide	60 ppm	40 - 60 ppm	70 ppm
Nitric Oxide	0.6 ppm	0.4 - 0.6 ppm	0.7 ppm
Nitrogen Dioxide	0.4 ppm	0.3 - 0.4 ppm	0.5 ppm
Sulfur Dioxide	0.5 ppm	0.4 - 0.6 ppm	0.7 ppm
Total Hydrocarbons	20 ppm	12 - 17 ppm	20 ppm
Total Oxidants	0.3 ppm	0.2 - 0.3 ppm	0.4 ppm

Values of concentrations of air contaminants as established pursuant to the Occupational Safety and Health Act of 1970, Public Law 91-596 for manned tunnels are as follows:

Contaminant	Allowable Concentration	Time Weighted Average Limits
CO	50 ppm	75.0 ppm
NO	25 ppm	37.5 ppm
NO_2	5 ppm	10.0 ppm
HCHO	3 ppm	6.0 ppm
Particulates	5 mg/m^3	10.1

Threshold Limit Values (TLV) and Short Term Limits (STL) for unmanned tunnels as established by the American Industrial Hygiene Foundation, the Pennsylvania Division of Health and the Aero Medical Association are as follows:

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Pollutant	TLV	STL			
		5 min.	10 min.	15 min.	30 min.
CO	50 ppm	-	1500	1000	800
NO	25	-	-	-	-
NO_2	5	35	-	25	20
HCHO	2	5	-	-	-
Particulates	5 mg/m^3			-	-

Tentative Pollutant Concentration levels for manned and unmanned tunnels as recommended by the Mine Safety Appliances Research Corporation are as follows:

Pollutant	Manned Tunnels	Unmanned Safety Level	Tunnels Comfort Level
CO	75 ppm	500 ppm	1,000 ppm
NO	37.5	37.5	25
NO_2	10	5	1
HCHO	6	6	1
Particulates	10 mg/m^3	10 mg/m^3	-

FACILITIES FOR MEASURING POLLUTANTS

The technique used to obtain samples of pollutants in the air follows the method used by the Colorado State and Federal Environmental Agencies. It consists of evacuating the air out of an air tight box approximately 10" x 14" x 24" inside of which is a mylar bag with an opening to the outside of the box. As the air in the box is evacuated by a small battery-powered pump, the inner mylar bag expands and allows an air sample to enter.

The sample of air in the mylar bag is usually taken to a nearby highway maintenance building where a 110 volt source of electricity is available to operate the analyzers. An analysis is seldom made at the site because of the traffic congestion and the fact that the analyzers do not perform perfectly when powered by a portable generator.

The amounts of CO, NO_2, NO_x and hydrocarbons are determined using the following analyzers:

CO - Beckman IR 215A Infrared Analyzer (modified)

NO_2 - NO_x - Scientific Industries Portable Model 80

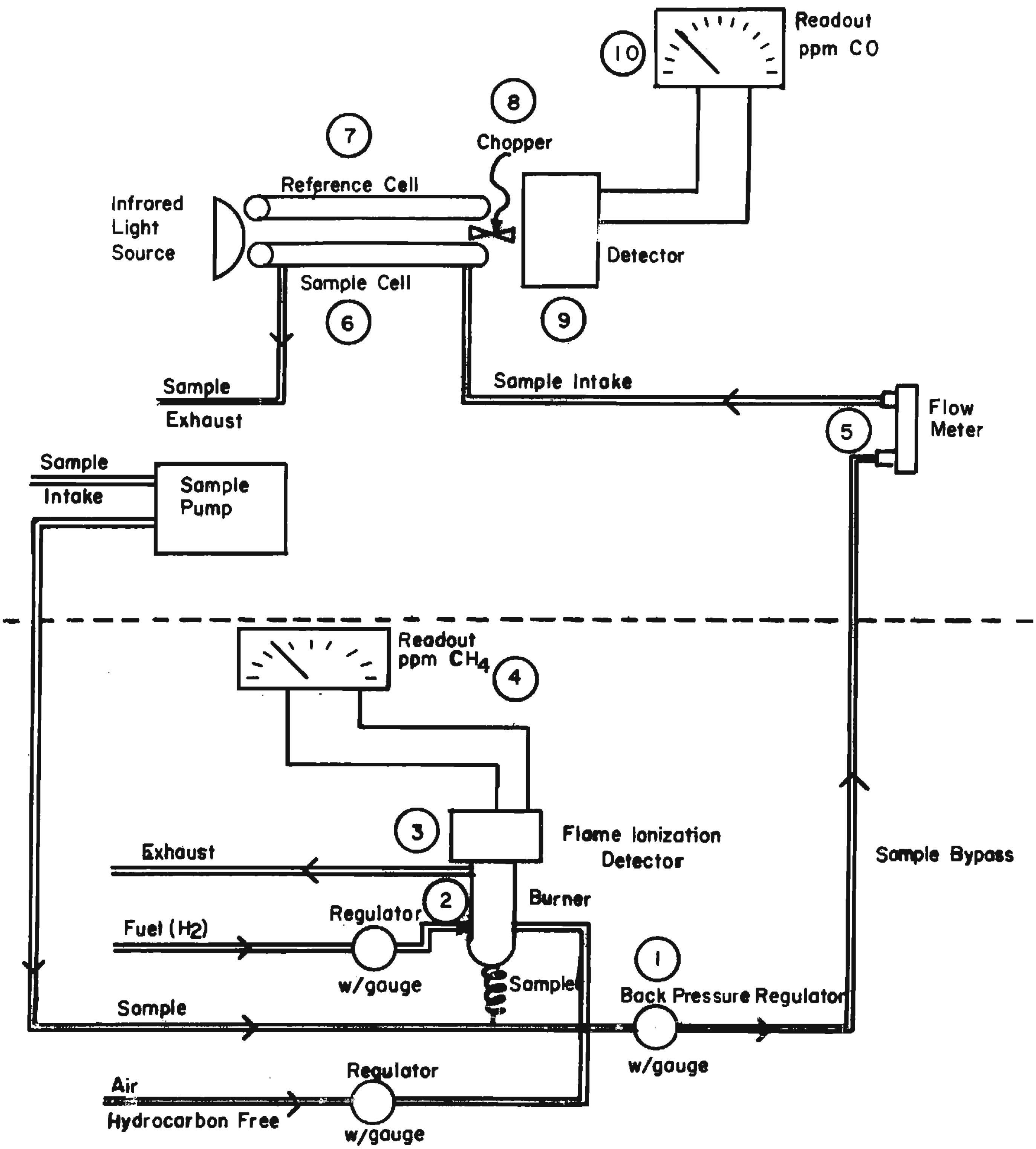
CH_4 - Beckman Model 400 Hydrocarbon Analyzer

Instruments were calibrated with gases of known content prepared by the Matheson Gas Products of Joliet, Illinois. Chemists and Technicians had previous experience with the operation of similar equipment from the Colorado High Altitude tests performed in 1964-65.

Figures 2 and 3 are sketches of the hookup for the CO, HC and NO_x analyzers.

FIGURE 2

CARBON MONOXIDE ANALYZER
(NONDISPERSIVE INFRARED ANALYZER)

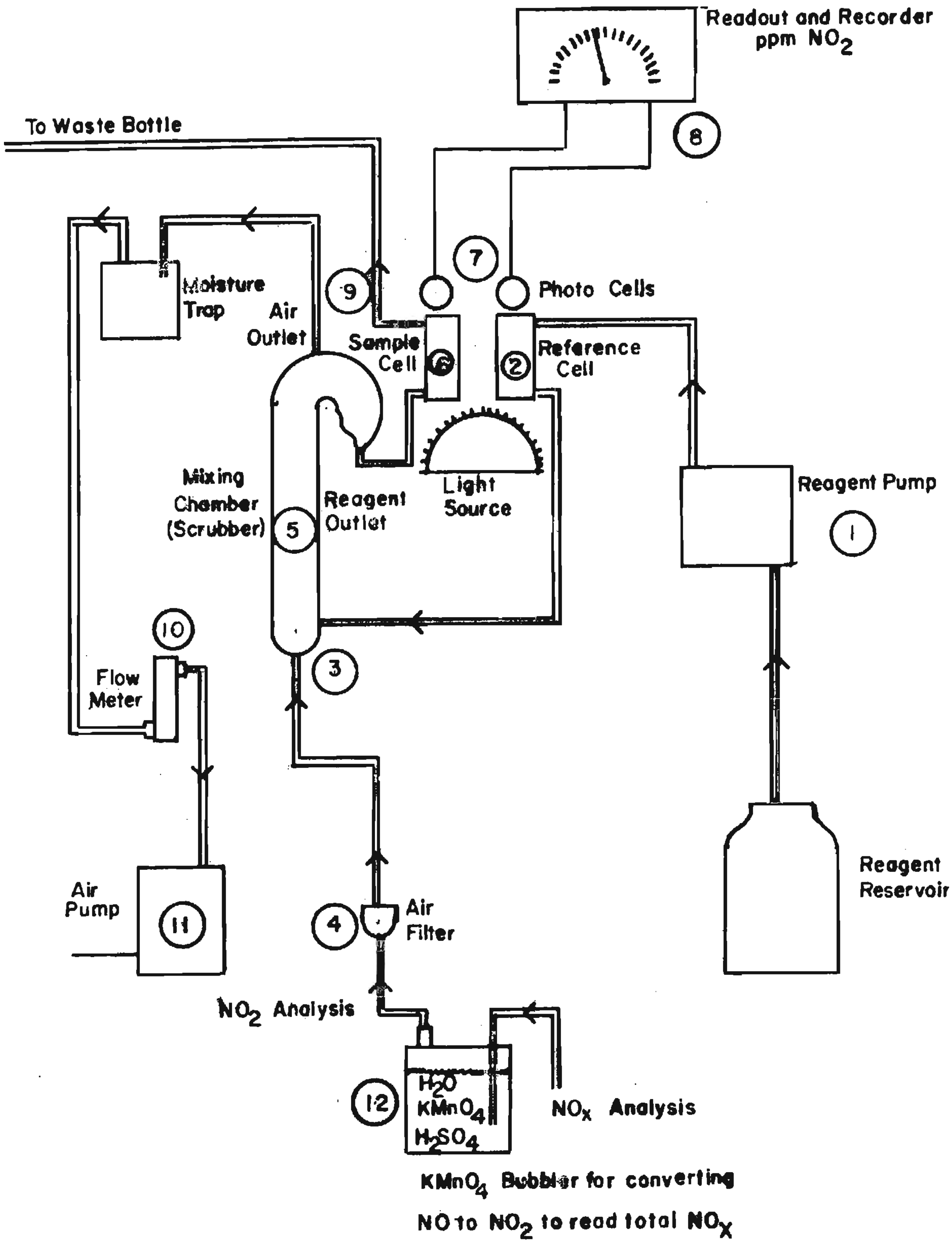


HYDROCARBON ANALYZER
(FLAME IONIZATION ANALYZER)

FIGURE 3

NO$_2$ – NO$_X$ ANALYZER

(VISIBLE ABSORPTION ANALYZER)



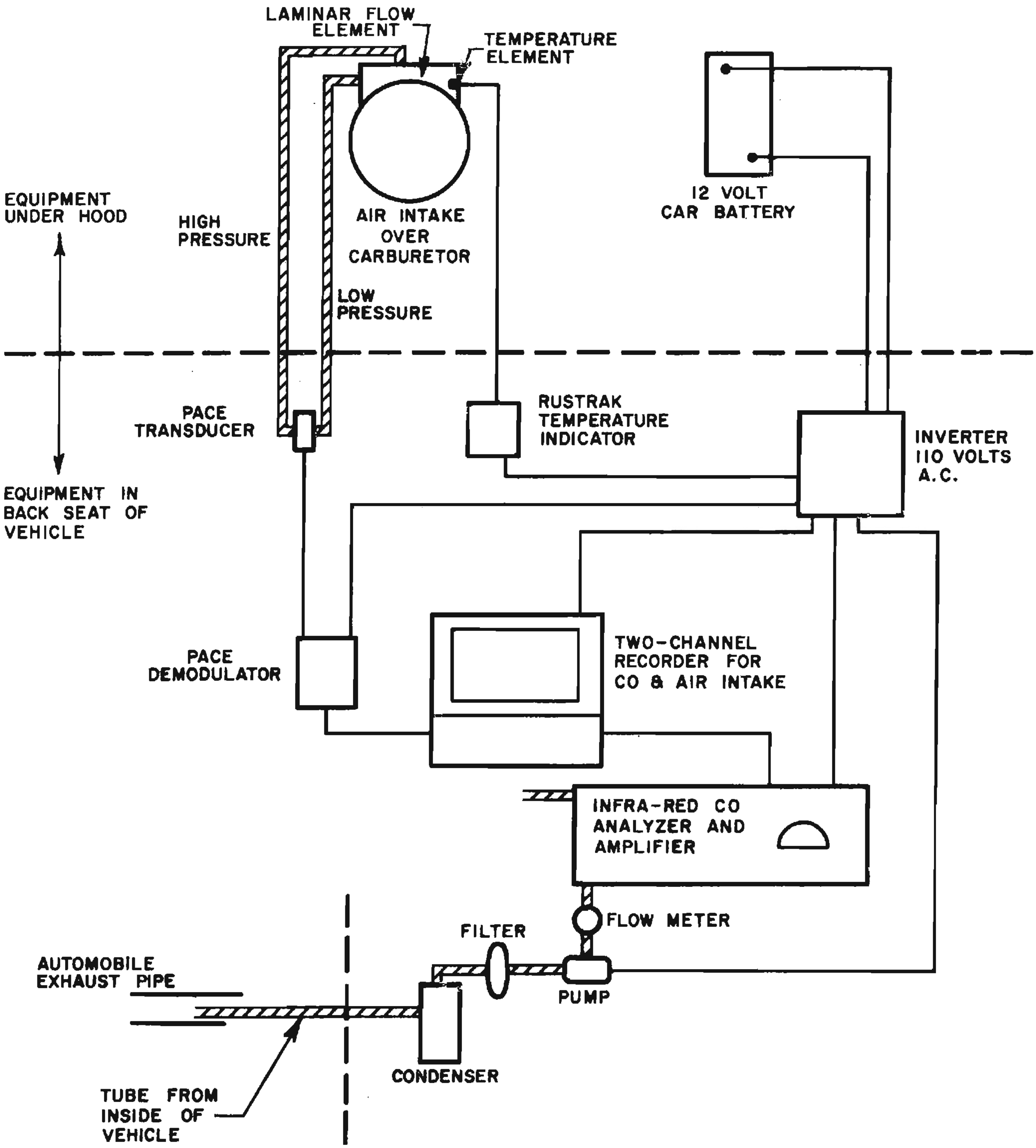
Sampling of the exhaust gas from vehicles was accomplished by a different procedure since high concentrations of CO have a tendency to revert to CO_2 and other products more readily than low concentrations. A sampling tube was inserted 2 feet into the tail pipe of the vehicles, and continuous measurements were taken inside the vehicle with portable analyzers. A sketch of the system used to measure the emission of CO from vehicles is shown as Figure 4.

TEST RESULTS

After an investigation of the tunnels in Colorado, New Mexico, Wyoming and Utah, eleven sites were selected. Officials from the New Mexico, Wyoming and Utah Highway Departments were very helpful in supplying data and offering to help, but it appeared that the extra cost of going to the tunnel sites outside of Colorado would not be justified. In fact, many of the tunnels in Colorado would not contribute information of the type needed. There was an abundance of short tunnels having very light traffic and a shortage of long tunnels with heavy traffic, from which to select samples. This situation was anticipated when the project was envisioned. Data from a long tunnel at high elevation came from the Eisenhower Memorial Tunnel under the Continental Divide after it was completed in March 1973.

FIGURE 4

SKETCH OF INSTRUMENTATION USED TO OBTAIN CARBON MONOXIDE EMISSION DATA



Results of the tests are itemized on pages 16 through 28. The Glenwood Springs Canyon Tunnels, Idaho Springs Tunnels and Stapleton Field Tunnels are all one-way tunnels with smooth walls. The Stapleton Field Tunnels are 3 lanes each way. The Clear Creek Tunnels are two-way tunnels with rough interiors covered with pneumatic applied concrete. Temperature and humidity readings were not taken inside the tunnels in some cases. Minus readings in the WIND Column indicate a direction "against traffic."

TABLE I

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

TUNNEL ID	ALT	GR	TUN AREA	TUN LNTH	AVG VEH SPD	DATE	TIME	ENTRY DIST	VEH/ HR.	WIND OUT	WIND IN	TEMP OUT	TEMP IN	HUMID OUT	HUMID IN	CO	PARTS PER MILLION HC	NO-2	NO	NO-X	1-2 WAY	S-R WALL
CLEAR CR =1	5818	3.0	522	859	40	10472	1030	302	60	010	005	002		90		4.0	6.0	.030	.020	.050	2	R
CLEAR CR =1	5818	3.0	522	859	40	10472	1045	82	48	010	005	002		90		7.0	4.0	.050	.160	.210	2	R
CLEAR CR =1	5818	3.0	522	859	40	91671	1315	400	108	000	000	035		90		8.0		.065	.095	.160	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1450	150	222	000	000	067	062	28	28	5.0	1.5	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1450	300	222	000	000	067	062	28	28	8.0	2.0	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1450	450	222	000	000	067	062	28	28	11.0	2.5	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1450	600	222	000	000	067	062	28	28	13.0	4.0	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1450	750	222	000	000	067	062	28	28	18.0	3.0	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1155	750	284	002	001	065	058	27	32	8.0	6.0	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1155	600	284	002	001	065	058	27	32	6.0	2.3	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1155	450	284	002	001	065	058	27	32	5.5	1.5	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1155	300	284	002	001	065	058	27	32	5.0	1.0	*.000	*.000	*.000	2	R
CLEAR CR =1	5818	3.0	522	859	40	41072	1155	150	284	002	001	065	058	27	32	4.5	1.0	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	91671	1100	230	128	001	000	030		15		15.0	7.0	.100	.150	.250	2	R
CLEAR CR =2	6449	4.7	530	1069	40	91671	1115	490	140	001	000	030		10		10.0	4.5	.075	.055	.130	2	R
CLEAR CR =2	6449	4.7	530	1069	40	110571	1530	150	216	000	002	030		10		10.0	16.0	.050	.060	.110	2	R
CLEAR CR =2	6449	4.7	530	1069	40	111271	1220	30	138	002	000	066		32		32.0	6.0	.030	.210	.240	2	R
CLEAR CR =2	6449	4.7	530	1069	40	111271	1235	280	168	001	000	066		75		**75.0	11.0	.140	.999	.999	2	R
CLEAR CR =2	6449	4.7	530	1069	40	111271	1250	530	84	001	000	066		20		20.0	6.0	.030	.180	.210	2	R
CLEAR CR =2	6449	4.7	530	1069	40	122071	1320	280	240	005	003	052		40		40.0	10.0	.050	.330	.380	2	R
CLEAR CR =2	6449	4.7	530	1069	40	122071	1330	30	132	005	003	052		15		15.0	25.0	.030	.050	.080	2	R
CLEAR CR =2	6449	4.7	530	1069	40	10472	1300	30	36	012	010	007		03		3.0	5.0	.020	.010	.030	2	R
CLEAR CR =2	6449	4.7	530	1069	40	10472	1315	280	66	012	010	007		03		3.0	4.0	.020	.010	.030	2	R
CLEAR CR =2	6449	4.7	530	1069	40	110971	1410	500	156	000	000	055		15		15.0		.020	.080	.100	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1343	150	271	000	000	067	062	28	28	10.0	2.0	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1343	300	271	000	000	067	062	28	28	8.5	2.0	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1343	450	271	000	000	067	062	28	28	9.0	1.5	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1343	600	271	000	000	067	062	28	28	11.5	1.3	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1343	750	271	000	000	067	062	28	28	14.0	1.6	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1010	100	208	003	001	065	058	27	32	3.0	1.7	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1010	200	208	003	001	065	058	27	32	3.5	1.5	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1010	300	208	003	001	065	058	27	32	3.0	1.5	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1010	450	208	003	001	065	058	27	32	3.0	1.5	*.000	*.000	*.000	2	R
CLEAR CR =2	6449	4.7	530	1069	40	41072	1010	550	208	003	001	065	058	27	32	2.5	1.9	*.000	*.000	*.000	2	R
CLEAR CR =3	6515	2.6	530	726	40	110571	1505	230	180	000	002	032		80		9.0	18.0	.070	.070	.140	2	R

NOTE * = NO DATA
-WIND = WIND OPPOSITE DIRECTION OF TRAFFIC(1-WAY TUNNELS)
R-S WALL = SMOOTH OR ROUGH TUNNEL WALLS
** Unusually high background CO when this sample was taken. Strong, low temperature inversion over area at the time. High traffic volume gave high concentration.

TABLE I

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

TUNNEL ID	ALT	GR	TUN AREA	TUN LNTH	AVG VEH SPD	DATE	TIME	ENTRY DIST	VEH/ HR.	WIND OUT	WIND IN	TEMP OUT	TEMP IN	HUMID OUT	HUMID IN	PARTS PER MILLION CO	HC	NO-2	NO	NO-X	1-2 WAY	S-R WALL
CLEAR CR =3	6515	2.6	530	726	40	110571	1515	380	186	000	002	032		80		7.0	15.0	.060	.050	.110	2	R
CLEAR CR =3	6515	2.6	530	726	40	110971	1340	375	78	000	000	055		40		15.0	15.0	.060	.440	.500	2	R
CLEAR CR =3	6515	2.6	530	726	40	122071	1350	330	180	010	007	052		35		17.0	3.0	.030	.090	.120	2	R
CLEAR CR =3	6515	2.6	530	726	40	10472	1245	300	84	012	012	007		87		3.0	5.0	.020	.020	.040	2	R
CLEAR CR =3	6515	2.6	530	726	40	110971	1355	200	84	000	000	055		40		5.0		.030	.070	.100	2	R
CLEAR CR =5	6980	3.9	562	411	40	92071	1120	200	96	000	000	048		38		5.0	2.5	.070	.015	.085	2	R
CLEAR CR =5	6980	3.9	562	411	40	122171	1020	362	114	005	003	037		68		6.0	3.0	.030	.150	.180	2	R
CLEAR CR =6	7064	4.0	562	588	40	110971	1115	300	60	000	000	050		40		25.0	22.0	.035	.215	.250	2	R
CLEAR CR =6	7064	4.0	562	588	40	110971	1125	300	114	000	000	050		40		18.0	24.0	.030	.130	.160	2	R
CLEAR CR =6	7064	4.0	562	588	40	110971	1135	150	36	000	000	050		40		8.0	28.0	.030	.070	.100	2	R
CLEAR CR =6	7064	4.0	562	588	40	111271	940	300	96	001	002	048		35		5.0	6.0	.020	.180	.200	2	R
CLEAR CR =6	7064	4.0	562	588	40	111271	950	150	42	001	002	048		35		5.0	5.0	.030	.080	.110	2	R
CLEAR CR =6	7064	4.0	562	588	40	111271	1000	0	102	001	002	048		35		15.0	6.5	.020	.060	.080	2	R
CLEAR CR =6	7064	4.0	562	588	40	122171	1035	262	96	003	000	037		68		5.0	3.0	.030	.040	.070	2	R
CLEAR CR =6	7064	4.0	562	588	40	122171	1045	412	90	003	000	037		68		5.0	3.0	.030	.040	.070	2	R
CLEAR CR =6	7064	4.0	562	588	40	11572	1400	300	132	010	003	045		36		4.0	1.0	.030	.030	.060	2	R
CLEAR CR =6	7064	4.0	562	588	40	11572	1415	412	156	010	003	045		36		6.0	1.5	.030	.020	.050	2	R
CLEAR CR =6	7064	4.0	562	588	40	41372	1400	558	154	002	000	065	060	44	45	3.0	2.0	*.000	*.000	*.000	2	R
CLEAR CR =6	7064	4.0	562	588	40	41372	1400	368	154	002	000	065	060	44	45	4.0	2.2	*.000	*.000	*.000	2	R
CLEAR CR =6	7064	4.0	562	588	40	41372	1400	288	154	002	000	065	060	44	45	2.0	1.5	*.000	*.000	*.000	2	R
CLEAR CR =6	7064	4.0	562	588	40	41372	1400	188	154	002	000	065	060	44	45	1.0	1.5	*.000	*.000	*.000	2	R
CLEAR CR =6	7064	4.0	562	588	40	41372	1400	88	154	002	000	065	060	44	45	2.0	2.0	*.000	*.000	*.000	2	R

NOTE * = NO DATA
-WIND = WIND OPPOSITE DIRECTION OF TRAFFIC(1-WAY TUNNELS)
R-S WALL = SMOOTH OR ROUGH TUNNEL WALLS

TABLE I

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

TUNNEL ID	ALT	GR	TUN AREA	TUN LNTH	AVG VEH SPD	DATE	TIME	ENTRY DIST	VEH/ HR.	WIND OUT	WIND IN	TEMP OUT	TEMP IN	HUMID OUT	HUMID IN	PARTS PER MILLION CO	HC	NO-2	NO	NO-X	1-2 WAY	S-R WALL
NO NAME EB	5796	2.7	655	1044	50	22072	915	520	108	000	002	033		65		10.0	4.0	.010	.140	.150	1	S
NO NAME EB	5796	2.7	655	1044	50	22072	1120	395	144	000	002	046		38		6.0	4.0	.010	.130	.140	1	S
NO NAME EB	5796	2.7	655	1044	50	22072	1135	260	162	000	002	046		38		6.0	4.0	.020	.030	.050	1	S
NO NAME EB	5796	2.7	655	1044	50	22072	1311	395	156	000	002	050		30		6.0	3.0	.020	.060	.080	1	S
NO NAME EB	5796	2.7	655	1044	50	22072	1328	135	186	000	002	050		30		4.5	7.0	.020	.040	.060	1	S
NO NAME EB	5796	2.7	655	1044	50	22072	1335	260	162	000	002	050		30		4.5	4.0	.020	.030	.050	1	S
NO NAME EB	5796	2.7	655	1044	50	22172	845	395	132	000	002	036		64		4.0	4.0	.010	.080	.090	1	S
NO NAME EB	5796	2.7	655	1044	50	22172	905	135	102	000	002	036		64		2.0	3.0	.010	.050	.060	1	S
NO NAME WB	5799	-3.0	655	1044	50	21972	1445	260	216	-02	-02	058		34		2.5	3.0	.010	.010	.020	1	S
NO NAME WB	5799	-3.0	655	1044	50	22072	850	135	42	000	002	033		65		1.0	3.0	.010	.010	.020	1	S
NO NAME WB	5799	-3.0	655	1044	50	22072	1100	455	30	000	002	046		38		3.0	4.0	.010	.030	.040	1	S
NO NAME WB	5799	-3.0	655	1044	50	22072	1505	260	180	-05	-02	060		40		3.5	3.0	.020	.010	.030	1	S
NO NAME WB	5799	-3.0	655	1044	50	22072	1518	520	216	-05	-02	060		40		4.5	3.0	.010	.010	.020	1	S
NO NAME WB	5799	-3.0	655	1044	50	22072	1531	395	180	-05	-02	060		40		3.5	3.0	.010	.010	.020	1	S
NO NAME WB	5799	-3.0	655	1044	50	22172	830	135	72	000	002	036		64		2.5	3.0	.010	.030	.040	1	S
NO NAME WB	5799	-3.0	655	1044	50	21972	1455	520	234	-02	-02	058		34		2.5	15.0	*.000	*.000	*.000	1	S
NO NAME WB	5799	-3.0	655	1044	50	21972	1505	395	324	-02	-02	058		34		5.0	4.0	*.000	*.000	*.000	1	S
NO NAME WB	5799	-3.0	655	1044	50	21972	1625	260	102	-02	-02	049		34		1.0	2.0	*.000	*.000	*.000	1	S
IDAHO SP EB	7380	-1.2	631	681	50	92471	1025	300	200	000	001	065		39		5.0	1.5	.080	.020	.100	1	S
IDAHO SP EB	7380	-1.2	631	681	50	92471	1050	150	264	000	001	065		39		5.0	.9	.095	.005	.100	1	S
IDAHO SP EB	7380	-1.2	631	681	50	92471	1305	531	272	-02	007	072		28		10.0	1.5	.080	.005	.085	1	S
IDAHO SP EB	7380	-1.2	631	681	50	92471	1320	631	222	-02	007	072		28		7.0	1.5	.075	.010	.085	1	S
IDAHO SP EB	7380	-1.2	631	681	50	92471	1410	200	330	-04	007	069		34		10.0	1.6	.110	.050	.160	1	S
IDAHO SP EB	7380	-1.2	631	681	50	92471	1420	100	414	-08	004	069		34		10.0	1.7	.115	.070	.185	1	S
IDAHO SP EB	7380	-1.2	631	681	50	92471	1450	381	294	-08	005	068		34		13.0	4.0	.110	.080	.190	1	S
IDAHO SP EB	7380	-1.2	631	681	50	102471	1320	381	606	-03	002	066		32		8.0	1.2	.050	.060	.110	1	S
IDAHO SP EB	7380	-1.2	631	681	50	102471	1335	481	666	-03	002	066		32		8.0	2.3	.060	.130	.190	1	S
IDAHO SP EB	7380	-1.2	631	681	50	102471	1430	200	660	-05	003	064		38		6.0	1.5	.075	.145	.220	1	S
IDAHO SP EB	7380	-1.2	631	681	50	102471	1445	100	792	-05	003	064		38		10.0	1.9	.070	.220	.290	1	S
IDAHO SP EB	7380	-1.2	631	681	50	102471	1520	581	894	-05	003	064		38		12.0	2.5	.065	.185	.250	1	S
IDAHO SP EB	7380	-1.2	631	681	50	102471	1615	300	1290	-02	005	062		32		17.0	2.1	.085	.280	.365	1	S
IDAHO SP EB	7380	-1.2	631	681	50	102471	1630	481	1092	000	005	062		32		11.0	1.5	.085	.225	.310	1	S
IDAHO SP EB	7380	-1.2	631	681	50	11572	1620	521	936	008	010	040		37		3.0	1.0	.020	.010	.030	1	S
IDAHO SP EB	7380	-1.2	631	681	50	11572	1635	330	1158	008	010	040		37		4.0	2.0	.030	.020	.050	1	S
IDAHO SP EB	7380	-1.2	631	681	50	11572	1650	160	1080	008	010	040		37		5.0	1.0	.020	.040	.060	1	S

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TABLE I

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

TUNNEL ID	ALT	GR	TUN AREA	TUN LNTH	AVG VEH SPD	DATE	TIME	ENTRY DIST	VEH/ HR.	WIND OUT	WIND IN	TEMP OUT	TEMP IN	HUMID OUT	HUMID IN	CO	PARTS PER MILLION HC	NO-2	NO	NO-X	1-2 WAY	S-R WALL
IDAHO SP EB	7380	-1.2	631	681	50	102471	1645	581	1302	000	005	062		32		9.0	3.0	*.000	*.000	*.000	1	S
IDAHO SP EB	7381	-1.2	631	681	45	41372	1129	500	208	004	003	064	058	44	46	5.0	2.2	*.000	*.000	*.000	1	S
IDAHO SP EB	7381	-1.2	631	681	45	41372	1129	400	208	004	003	064	058	44	46	3.0	2.7	*.000	*.000	*.000	1	S
IDAHO SP EB	7381	-1.2	631	681	45	41372	1129	300	208	004	003	064	058	44	46	4.0	1.6	*.000	*.000	*.000	1	S
IDAHO SP EB	7381	-1.2	631	681	45	41372	1129	200	208	004	003	064	058	44	46	2.0	1.4	*.000	*.000	*.000	1	S
IDAHO SP EB	7381	-1.2	631	681	45	41372	1129	100	208	004	003	064	058	44	46	2.0	1.4	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	92071	1315	350	228	000	004	057		30		3.0	1.5	.080	.040	.120	1	S
IDAHO SP WB	7387	1.2	631	741	50	92071	1330	200	240	000	004	057		30		2.0	1.0	.070	.020	.090	1	S
IDAHO SP WB	7387	1.2	631	741	50	92071	1430	561	324	000	004	057		30		3.0	1.0	.080	.060	.140	1	S
IDAHO SP WB	7387	1.2	631	741	50	92071	1445	641	366	000	004	057		30		8.0	1.5	.080	.060	.140	1	S
IDAHO SP WB	7387	1.2	631	741	50	122171	1200	391	306	005	010	056		20		10.0	3.0	.030	.080	.110	1	S
IDAHO SP WB	7387	1.2	631	741	50	11572	1535	195	336	-08	-10	042		22		8.0	3.0	.020	.060	.080	1	S
IDAHO SP WB	7387	1.2	631	741	50	11572	1520	356	246	-08	-10	042		22		5.0	1.0	.010	.040	.050	1	S
IDAHO SP WB	7387	1.2	631	741	50	122171	1210	541	330	005	010	056		20		10.0	2.0	.030	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	122171	1220	741	156	005	010	056		20		10.0	2.0	.035	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	122171	1430	541	192	-10	-03	056		20		16.0	3.0	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	122171	1440	741	258	-10	-03	056		20		6.0	2.0	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1045	216	223	-04	-03	065	058	40	37	3.0	2.7	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1045	466	223	-04	-03	065	058	40	37	4.0	1.6	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1045	516	223	-04	-03	065	058	40	37	2.0	1.4	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1045	616	223	-04	-03	065	058	40	37	2.0	1.4	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1002	216	212	-01	-04	066	060	25	26	15.0	2.7	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1002	366	212	-01	-04	066	060	25	26	12.0	2.0	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1002	516	212	-01	-04	066	060	25	26	7.0	3.2	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1002	125	212	-01	-04	066	060	25	26	7.0	2.5	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1337	91	226	-03	-04	062	059	28	29	8.0	1.2	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1337	241	226	-03	-04	062	059	28	29	7.0	1.1	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1337	391	226	-03	-04	062	059	28	29	6.0	1.3	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1337	541	226	-03	-04	062	059	28	29	4.0	1.2	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1337	641	226	-03	-04	062	059	28	29	3.0	1.5	*.000	*.000	*.000	1	S
IDAHO SP WB	7387	1.2	631	741	50	41372	1045	116	223	-04	-03	065	058	40	37	5.0	2.2	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1137	150	1514	004	007	075	069	48	45	5.0	1.4	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1137	300	1514	004	007	075	069	48	45	4.0	1.7	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1137	450	1514	004	007	075	069	48	45	6.0	2.0	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1137	600	1514	004	007	075	069	48	45	5.5	2.3	*.000	*.000	*.000	1	S

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TABLE I

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

TUNNEL ID	ALT	GR	TUN AREA	TUN LNTH	AVG VEH SPD	DATE	TIME	ENTRY DIST	VEH/ HR.	WIND OUT	WIND IN	TEMP OUT	TEMP IN	HUMID OUT	HUMID IN	CO	PARTS PER MILLION HC	NO-2	NO	NO-X	1-2 WAY	S-R WALL
STAPLETONEB	5251	.3	777	757	60	41772	1137	750	1514	004	007	075	069	48	45	7.0	1.9	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1307	150	1656	002	005	075	076	49	41	6.0	1.6	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1307	300	1656	002	005	075	076	49	41	6.0	1.8	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1307	450	1656	002	005	075	076	49	41	7.0	1.9	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1307	600	1656	002	005	075	076	49	41	9.0	2.0	*.000	*.000	*.000	1	S
STAPLETONEB	5251	.3	777	757	60	41772	1307	750	1656	002	005	075	076	49	41	10.0	2.0	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	100871	740	150	2124	000		040		89			5.0	.090	.390	.480	1	S
STAPLETONWB	5251	-.3	777	757	60	100871	755	50	2766	000		040		89			7.5	.100	.150	.250	1	S
STAPLETONWB	5251	-.3	777	757	60	101571	750	200	2280	-06	005	038		89		5.0	8.3	.070	.130	.200	1	S
STAPLETONWB	5251	-.3	777	757	60	101571	800	100	2400	-06	005	038		89		7.0	5.4	.080	.110	.190	1	S
STAPLETONWB	5251	-.3	777	757	60	101571	810	0	1728	-06	005	038		89		3.0	4.5	.070	.010	.080	1	S
STAPLETONWB	5251	-.3	777	757	60	101571	1055	550	1062	-04	005	044		73		7.0	6.0	.090	.150	.240	1	S
STAPLETONWB	5251	-.3	777	757	60	101571	1105	750	1140	-04	005	044		73		10.0	6.0	.090	.260	.350	1	S
STAPLETONWB	5251	-.3	777	757	60	120871	800	550	1680	004	010	000		99		5.0	4.0	.020	.130	.150	1	S
STAPLETONWB	5251	-.3	777	757	60	120871	815	750	1266	004	010	000		99		18.0	12.0	.020	.140	.160	1	S
STAPLETONWB	5251	-.3	777	757	60	120871	1015	350	648	005	008	008		96		8.0	6.0	.020	.080	.100	1	S
STAPLETONWB	5251	-.3	777	757	60	120871	1030	550	726	006	008	008		96		9.0	3.0	.020	.230	.250	1	S
STAPLETONWB	5251	-.3	777	757	60	92371	1205	200	1032							14.0	2.0	.075	.185	.260	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1010	157	769	000	008	074	067	08	26	3.0	1.9	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1010	307	769	000	008	074	067	08	26	3.0	3.2	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1010	457	769	000	008	074	067	08	26	6.0	2.7	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1010	607	769	000	008	074	067	08	26	7.0	2.6	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1010	682	769	000	008	074	067	08	26	5.0	2.7	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1102	7	996	002	008	073	069	49	45	2.0	1.4	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1102	157	996	002	008	073	069	49	45	4.0	1.0	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1102	307	996	002	008	073	069	49	45	5.0	1.0	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1102	457	996	002	008	073	069	49	45	5.0	1.4	*.000	*.000	*.000	1	S
STAPLETONWB	5251	-.3	777	757	60	41772	1102	607	996	002	008	073	069	49	45	6.0	1.8	*.000	*.000	*.000	1	S
CLEAR CR =1	5818	3.0	522	859	40	91571	1525	250	220	001	001	055		90		25.0	11.0	.130	.140	.270	2	R
CLEAR CR =1	5818	3.0	522	859	40	91671	1330	250	272	000	000	035		90		15.0	11.0	.075	.045	.120	2	R
CLEAR CR =1	5818	3.0	522	859	40	91671	1505	272	172	001	000	035		95		15.0	4.0	.090	[illegible]	.350	2	R
CLEAR CR =1	5818	3.0	522	859	40	111271	1415	440	126	001	000	071		05		13.0	5.5	.045	.135	.180	2	R
CLEAR CR =1	5818	3.0	522	859	40	111271	1425	220	210	001	000	071		05		18.0	6.0	.050	.470	.520	2	R
CLEAR CR =1	5818	3.0	522	859	40	122071	1130	82	144	010	005	048		45		11.0	4.5	.030	.220	.250	2	R
CLEAR CR =1	5818	3.0	522	859	40	122071	1140	302	192	010	005	048		45		20.0	5.2	.070	[illegible]	.720	2	R

NOTE * = NO DATA
-WIND = WIND OPPOSITE DIRECTION OF TRAFFIC(1-WAY TUNNELS)
R-S WALL = SMOOTH OR ROUGH TUNNEL WALLS

TABLE II

8941' Eisenhower Tunnel Date March 8, 1973 Tunnel Opened at 11:30 AM

	Noon 12:00	2		4		6		8		10	Midnite 12
Altimeter	29.93	29.92	29.93	29.93	29.93	29.94	29.95	29.96	29.96	29.96	29.96
E. Barometer	20.02	20.02	20.03	20.03	20.03	20.04	20.05	20.05	20.06	20.06	20.06
W. Barometer	19.92	19.92	19.93	19.93	19.93	19.94	19.94	19.94	19.95	19.95	19.95
Wind at:											
15,000' level	SW @ 26 mph										
East end	NE @ 7 mph	W5	W3	Var.	NW1	W1	Calm	NE2	0	0	SW4
500' fr E	E @ ½ mph	E½	E½	Calm	W3	W3	Calm	E1	E1	0	E1
Center	E @ 3 mph	E1	Calm	Calm	Calm	W2	Calm	E5	0	0	E4
500' fr W	E @ 5 mph	E5	E½	Calm	E2	Calm	E1	E2	0	0	E1
West end	SE @ 6 mph	SE9	E2	S5	W2	W2	NW3	NE3	0	NW2	W4
Temperature at:											
15,000' level	0°F										
East end	25°	29	28	22	22	17	17	16	17	16	18
500' fr E	47°	43	52	53	53	48	38	30	34	32	31
Center	47°	52	51	52	51	51	50	49	50	50	50
500' fr W	43°	44	45	46	44	44	44	44	43	42	42
West end	24°	31	22	24	22	18	18	18	18	17	17
Center Humidity	20%	20%	20%	20%	20%	20%	17%	15%	15%	15%	15%
Supply Fans	6 @ 100 hp	6 @ 100 →					4 @ 100 hp →				
Exhaust Fans	5 @ 100 hp	5 @ 100 →					4 @ 100 hp →				
Concentration:											
CO at E. end	20 ppm	45	28	16	35	35	8	9	6	3	2
CO 500' fr E	40	54	60	41	41	38	32	32	22	13	5
CO at center	130	73	54	65	63	51	25	32	27	23	20
CO 500' fr W	80	54	63	51	54	44	38	38	30	24	15
CO at W. end	12	20	25	20	28	25	25	22	15	10	5
HC at E. end	8	7	7	6	6	7	5	6	5	4	4
HC 500' fr E	10	7	8	7	6	6	8	8	6	5	4
HC at Center	22	9	11	11	7	7	8	8	7	5	7
HC 500' fr W	14	6	6	6	6	6	8	8	6	5	4
HC at W. end	6	5	5	5	4	5	8	8	6	4	3
NOx at E. end	.06	.10	.07	.08	.22	.12	.05	.05	.05	.05	.05
NOx 500' fr E	.08	.14	.18	.17	.21	.26	.12	.15	.11	.09	.11
NOx at Center	.27	.18	.23	.30	.29	.23	.11	.25	.14	.12	.16
NOx 500' fr W	.30	.24	.25	.19	.29	.20	.25	.28	.15	.11	.13
NOx at W. end	.05	.12	.12	.12	.13	.10	.05	.16	.10	.08	.08
Particulates at center				3485 µg/M³							

Traffic:												
Vehicles WB/hr.	293	298	250	225	253	214	193	175	148	134	122	118
Vehicles EB/hr.	355	338	342	347	533	402	234	138	110	92	72	60
Vehicles Total	648	636	592	572	786	616	427	313	258	226	194	178
% Gas Trucks	-	-	-	-	1						1.5%	-
% Diesel Trucks	-	-	-	-	3						5.2%	-

Speed:											
Average WB	23.6 mph	29.8	33.9	43.1	32.5	39.3	34.0	33.8	45.9	40.2	39.2
Average EB	29.6 mph	36.2	33.5	43.3	44.3	40.5	43.2	40.4	39.0	43.7	38.5

Remarks: Before tunnel was opened, CO=5ppm, HC=7, and NO_x=0.06. Wind was W 3mph outside tunnel, but it was E 5mph inside the tunnel (smoke stack effect).

8941' Eisenhower Tunnel - Noon TABLE II

Midnite Date March 9, 1973

12:00		2		4		6		8		10	12	
29.96	29.95	29.95	29.94	29.94	29.93	29.93	29.91	29.90	29.89	29.89	29.89	Altimeter
20.06	20.05	20.05	20.04	20.04	20.04	20.03	20.02	20.01	20.00	20.00	19.99	E. Barometer
19.95	19.94	19.94	19.93	19.93	19.93	19.92	19.91	19.90	19.90	19.90	19.90	W. Barometer
												Wind at:
								SW @ 15 mph				15,000' level
NW3	NE4	NE4	--	SE2	--	SW2	W1	0	W5	SW1	W1	East end
W1	E1	E1	--	E1	--	E1	E3	E2	0	0	0	500' fr E
0	E3	E3	--	E1	--	E5	E1	E1	0	0	0	Center
E2	E1	E1	--	E1	--	E3	E1	E5	E1	0	E1	500' fr W
SW2	SW4	SE4	--	SW4	--	SE6	S2	N2	NE1	SW3	0	West end
												Temperature at:
								5°F				15,000' level
17	19	18	--	14	--	10	22	25	26	31	25	East end
34	34	36	--	30	--	25	30	30	34	35	38	500' fr E
50	50	49	--	49	--	44	45	46	48	48	44	Center
42	41	41	--	40	--	40	40	40	39	40	40	500' fr W
18	18	17	--	14	--	14	22	24	26	27	26	West end
15%		15%		12%		23%		17%		13%	13%	Center Humidity
4 @ 100 →								6 @ 100				Supply Fans
4 @ 100 →								5 @ 100 →		6 @ 100		Exhaust Fans
												Concentration:
2	2	2	2	2	1	0	11	11	12	17	18	CO at E. end
5	5	5	5	5	10	15	12	31	24	57	68	CO 500' fr E
15	10	5	5	5	7	8	22	60	160	83	100	CO at center
10	7	4	5	6	8	10	29	56	27	60	62	CO 500' fr W
3	2	1	2	4	4	5	16	15	11	26	26	CO at W. end
2	--	3	3	2.4	2	2	6	4	3	4	6	HC at E. end
3	5.5	4	4	3.1	3	4	5	9	6	8	12	HC 500' fr E
4	--	4	4	4.4	4	4	4	12	15	7	15	HC at Center
3	5.0	3	3	3.0	3	3	4	6	5	7	9	HC 500' fr W
2	--	2	2	2.7	3	3	3	7	3	4	5	HC at W. end
.05	--	.05	.05	.05	.05	.05	.10	.08	.08	.09	.11	NOx at E. end
.06	.23	.09	.08	.07	.08	.09	.12	.09	.15	.19	.20	NOx 500' fr E
.09	--	.12	.09	.07	.12	.20	.30	.24	.44	.35	.33	NOx at Center
.08	.20	.11	.09	.07	.13	.18	.32	.28	.29	.25	.25	NOx 500' fr W
.06	--	.07	.08	.10	.09	.04	.14	.11	.09	.11	.14	NOx at W. end
1000 µg/M³									2126 µg/M³			Particulates at center
												Traffic:
88	38	42	21	28	54	75	123	482	574	323	314	Vehicles WB/hr.
27	23	17	21	20	17	46	60	261	170	245	248	Vehicles EB/hr.
115	61	59	42	48	71	121	183	743	744	568	562	Vehicles Total
--	--	--	--	--	--	--	--	1%	--	--	--	% Gas Trucks
--	--	--	--	--	--	--	--	2%	--	--	--	% Diesel Trucks
												Speed:
38.6	34.3	40.9	35.6	35.3	35.6	41.0	41.9	31.3	38.7	35.8	37.0	Average WB
44.6	41.6	40.2	38.7	27.6	51.1	44.2	42.9	43.9	43.8	43.4	36.7	Average EB
												Remarks:

Noon 12:00		2		4		6		8		10	Midnite 12	TABLE II
				Date March 9, 1973			8941' Eisenhower Tunnel					
29.88	29.88	29.87	29.87	29.86	29.85	29.84	29.83	29.83	29.84	29.84	29.85	Altimeter
19.98	19.98	19.97	19.97	19.97	19.96	19.95	19.95	19.95	19.94	19.95	19.95	E. Barometer
19.88	19.88	19.87	19.86	19.86	19.85	19.84	19.83	19.84	19.84	19.84	19.84	W. Barometer
												Wind at:
						SW @ 15 mph						15,000' level
SW3	SW4	SW2	W5	NW2	N1	0				SE3	SE3	East end
E½	0	0	W1	0	0	0				W1	W1	500' fr E
E½	0	0	0	0	0	0				0	E1	Center
E½	E1	E1	W1	W2	W3	W1				0	W4	500' fr W
SW5	SW4	SW7	N2	SW2	NE2	N1				0	0	West end
												Temperature at:
					5°F							15,000' level
32	38	32	28	28	23	22				20	20	East end
42	43	45	47	45	45	44				40	40	500' fr E
50	50	50	50	50	50	50			43	43	50	Center
41	43	42	32	41	40	38				--	33	500' fr W
30	34	30	24	29	26	25			Snowing	--	20	West end
23%	28%	33%	50%	54%	52%	52%			28%		20%	Center Humidity
6 @ 100 hp		6 @ 100 →								6 @ 100 hp →		Supply Fans
6 @ 100 hp		5 @ 100 →								4 @ 100 hp →		Exhaust Fans
												Concentration:
13	23	21	19	50	17	3				5	5	CO at E. end
70	61	65	68	100	91	18				28	30	CO 500' fr E
70	44	77	--	91	113	52			10	33	40	CO at center
80	80	92	70	135	110	75				7	12	CO 500' fr W
38	63	32	19	9	14	37				3	3	CO at W. end
5	6	6	7	7	7	3				2	4	HC at E. end
9	10	11	12	10	15	5				6	11	HC 500' fr E
8	7	11	--	11	14	11			4	29	5	HC at Center
8	9	12	8	14	11	[illegible]				2	3	HC 500' fr W
5	8	6	4	4	5	7				2	2	HC at W. end
.09	.19	.13	.11	.20	.13	.07				.10	.08	NOx at E. end
.21	.23	.46	.21	.25	.24	.11				.11	.21	NOx 500' fr E
.25	.26	.31	--	.32	.41	.19			.13	.16	.44	NOx at Center
.23	.28	.40	.22	.33	.31	.37				.10	.20	NOx 500' fr W
.15	.23	.20	.13	.08	.09	.14				.08	.11	NOx at W. end
	2126 µg/M^3						--	--	--	--	--	Particulates at center
												Traffic:
286	293	316	401	425	271	140	12	48	12	161	126	Vehicles WB/hr.
230	335	410	432	680	274	82	151	114	268	408	111	Vehicles EB/hr.
516	628	726	833	1105	545	222	163	162	280	569	237	Vehicles Total
2%	--	--	1%	--	--	--	--	--	--	--	--	% Gas Trucks
3%	--	--	3%	--	--	--	--	--	--	--	--	% Diesel Trucks
												Speed:
41.8	39.5	41.7	34.2	--	--	20 mph (Intermittant)				45.5	42.0	Average WB
41.8	40.6	42.7	42.7	--	--	"	"	"		36.7	40.1	Average EB

Remarks: Snow storm on the roadway west of the tunnel caused so many accidents that road was closed. All vehicles and personnel were kept out of the tunnel until 9:00 PM. EB traffic only passed between 9 and 10:00. Tunnel open to EB and WB at 10:00 PM.

8941' Eisenhower Tunnel

TABLE II

Date March 10, 1973

Midnite 12:00		2		4		6		8		10	Noon 12	
29.85	29.84	29.83	29.83	29.83	29.84	29.85	29.85	29.86	29.85	29.84	29.83	Altimeter
19.95	19.95	19.95	19.94	19.93	19.93	19.94	19.95	19.95	19.95	19.95	19.94	E. Barometer
19.94	19.83	19.84	19.84	19.83	19.83	19.84	19.85	19.85	19.85	19.85	19.85	W. Barometer
												Wind at:
								N @ 6mph				15,000' level
W6	--	0	--	0	E2	NW3	SW3	SW2	0	0	0	East end
E1	--	NE6	--	NE2	W1	0	E1	0	0	E1	0	500' fr E
0	--	E1	--	E2	E2	E4	--	--	--	--	--	Center
E1	--	0	--	E3	E3	E2	E1	W2	W3	W3	E1	500' fr W
NE1	--	E2	--	E2	E3	E1	E4	NE4	E4	SE1	0	West end
												Temperature at:
								7°F				15,000' level
20	--	13	--	--	11	13	15	14	19	20	30	East end
31	--	26	--	--	24	25	20	24	27	30	35	500' fr E
50	--	43	--	44	46	48	46	43	44	44	44	Center
37	--	36	--	--	33	34	35	35	33	33	37	500' fr W
18	--	16	--	--	14	11	10	13	16	18	30	West end
21%	--	28%	--	--	23%	23%	--	13%	14%	14%	14%	Center Humidity
4 @ 100 →		2 @ 100 →				4 @ 100 →		6 @ 100 →				Supply Fans
4 @ 100 →		2 @ 100 →				5 @ 100 →		5 @ 100 →				Exhaust Fans
												Concentration:
5	10	12	7	3	3	0	3	16	10	32	62	CO at E. end
32	27	18	16	12	15	20	20	60	43	47	95	CO 500' fr E
70	60	48	30	15	20	35	97	120	108	110	130	CO at center
32	30	25	18	12	15	22	60	124	92	158	135	CO 500' fr W
15	20	25	15	7	9	10	17	125	7	25	21	CO at W. end
9	4	3	3	2	2	2	2	5	3	5	8	HC at E. end
17	5	4	4	3	3	3	6	11	6	6	10	HC 500' fr E
20	8	8	5	3	4	4	7	10	11	10	10	HC at Center
18	7	4	3	3	4	5	6	12	10	14	11	HC 500' fr W
--	4	3	2	2	2	3	3	5	3	4	4	HC at W. end
.09	.09	.10	.09	.10	.05	.10	.06	.14	.08	.10	.20	NOx at E. end
.15	.11	.10	.12	.23	.10	.13	.12	.16	.15	.14	.29	NOx 500' fr E
.41	.18	.18	.14	.25	.12	.24	.30	.31	.33	.31	.42	NOx at Center
.30	--	.13	.18	.18	.10	.19	.21	.43	.35	.31	.42	NOx 500' fr W
.13	.14	.13	.11	.12	.08	.11	.11	.14	.10	.09	.10	NOx at W. end
--	--	--	--	--	--	--	--	--	--	--	--	Particulates at center
												Traffic:
115	67	55	44	32	59	138	673	979	841	908	750	Vehicles WB/hr.
48	41	41	21	31	14	32	64	162	381	327	344	Vehicles EB/hr.
163	108	96	65	46	82	170	737	1141	1222	1235	1094	Vehicles Total
--	5%	--	--	--	--	--	--	--	1%	--	--	% Gas Trucks
--	9%	--	--	--	--	--	--	--	2%	--	--	% Diesel Trucks
												Speed:
42.0	40.5	33.9	35.3	--	--	37.7	41.8	33.1	35.1	35.2	32.7	Average WB
40.1	41.9	35.9	43.3	--	--	41.5	40.9	39.8	42.3	40.9	34.4	Average EB
												Remarks:

TABLE II

Date March 10, 1973 — 8941' Eisenhower Tunnel

Noon 12:00		2		4		6		8		10	Midnite 12	
29.83	29.82	29.82	29.81	29.81	29.81	29.81	29.81	29.81	29.81	29.81	29.81	Altimeter
19.94	19.93	19.93	19.92	19.92	19.91	19.90	19.90	19.90	19.90	19.90	19.90	E. Barometer
19.84	19.83	19.82	19.81	19.80	19.80	19.80	19.80	19.80	19.81	19.81	19.80	W. Barometer
												Wind at:
					N @ 6 mph							15,000' level
0	SW4	SW3	W4	W4	SW10	W4	SE4		SW10		W10	East end
0	0	0	0	0	W1	W1	W3		W2		NW2	500' fr E
0	0	0	W2	0	0	0	W2		0		W4	Center
E3	E2	W2	W1	W3	W2	W2	0		E1		0	500' fr W
SW3	0	S2	NE4	SW4	NW3	0	NW1		NW4		NW2	West end
												Temperature at:
					7°F							15,000' level
22	27	30	30	30	18	16	16	--	14	--	11	East end
34	37	38	40	44	42	42	44	--	43	--	44	500' fr E
44	45	46	46	46	45	41	44	--	40	--	40	Center
32	31	32	33	31	30	27	28	--	25	--	24	500' fr W
28	25	32	30	28	28	16	14	--	12	--	8	West end
15%	16%	16%	16%	15%	14%	24%	39%		37%		29%	Center Humidity
6 @ 100 →											→	Supply Fans
5 @ 100 →											→	Exhaust Fans
												Concentration:
72	76	82	50	132	100	70	30	22	15	13	10	CO at E. end
70	68	103	120	113	118	72	50	32	27	22	17	CO 500' fr E
123	90	80	80	106	85	53	58	50	40	30	20	CO at center
96	90	115	90	70	60	75	45	40	37	28	22	CO 500' fr W
10	4	15	30	4	9	25	9	7	5	5	6	CO at W. end
9	7	12	6	13	12	10	6	5	4	4	4	HC at E. end
9	6	14	12	11	13	10	7	6	5	5	6	HC 500' fr E
10	6	11	8	10	10	7	9	8	6	6	5	HC at Center
9	8	16	9	8	6	9	5	7	6	6	6	HC 500' fr W
4	1	5	4	3	3	5	2	3	4	4	4	HC at W. end
.17	.28	.30	.16	.39	.38	.29	.17	.12	.13	.11	.13	NOx at E. end
.20	.29	.42	.40	.50	.40	.29	.22	.16	.18	.13	.18	NOx 500' fr E
.37	.29	.28	.38	.36	.46	.23	.17	.21	.22	.16	.18	NOx at Center
.27	.27	.48	.23	.22	.18	.26	.18	.18	.14	.15	.10	NOx 500' fr W
.08	.08	.13	.15	.09	.08	.14	.10	.10	.08	.08	.10	NOx at W. end
		2915 µg/M³							1361 µg/M³			Particulates at center
												Traffic:
594	581	560	618	507	336	243	183	174	139	108	73	Vehicles WB/hr.
437	458	554	641	944	1007	404	257	168	145	82	79	Vehicles EB/hr.
1031	1039	1114	1259	1451	1343	647	440	342	284	190	152	Vehicles Total
				1%						2%		% Gas Trucks
				2%						7%		% Diesel Trucks
												Speed:
34.8	40.4	37.5	35.6	41.6	41.6	38.2	46.3		41.3		31.6	Average WB
34.2	35.4	34.9	35.3	35.0	37.6	41.4	41.5		47.7		37.6	Average EB
												Remarks:

Midnite   Date March 11, 1973   8941' Eisenhower Tunnel   Noon   TABLE II

12:00   2   4   6   8   10   12

29.81	29.81	29.81	29.82	29.83	29.84	29.84	29.85	29.85	29.86	29.87	29.87	Altimeter
19.90	19.90	19.91	19.91	19.92	19.93	19.93	19.93	19.93	19.94	19.95	19.96	E. Barometer
19.80	19.80	19.80	19.81	19.81	19.82	19.83	19.83	19.84	19.84	19.85	19.85	W. Barometer
												Wind at:
								NW @ 25 mph				15,000' level
--	W15		NW15		W10		NE4	NE6	NW4	NW4	SW8	East end
--	W4		SW2		W4		W2	W1	0	E1	E1	500' fr E
--	W4		W4		W2		0	E2	0	--	--	Center
--	W3		W3		W2		0	W2	E2	E2	E1	500' fr W
--	W3		SW2		Calm		0	NE5	NE4	NE4	SW6	West end
												Temperature at:
								13°F				15,000' level
--	10		12		12		20	22	23	29	34	East end
--	45		45		45		30	33	37	40	40	500' fr E.
--	39		38		37		50	50	45	45	46	Center
--	18		16		23		27	31	28	30	32	500' fr W
--	6		12		8		8	14	19	24	34	West end
--	27%		42%		48%		38%	38%	24%	24%	24%	Center Humidity
→ 2 @ 100 hp →							4 @ 100 hp →	7 @ 100 hp →				Supply Fans
→ 2 @ 100 hp →							4 @ 100 hp →	6 @ 100 hp →				Exhaust Fans
												Concentration:
7	5	7	10	8	7	5	4	18	35	15	26	CO at E. end
14	12	10	8	11	15	15	15	55	72	82	108	CO 500' fr E
19	18	13	7	9	11	32	75	150	112	85	100	CO at center
17	12	8	5	7	10	22	43	93	83	80	90	CO 500' fr W
6	5	3	0	1	2	3	5	20	11	37	63	CO at W. end
4	4	5	6	3	1	1	1	2	4	2	4	HC at E. end
6	6	6	6	3	3	2	2	4	5	7	9	HC 500' fr E
6	3	5	5	4	2	3	5	11	7	6	7	HC at Center
5	5	5	5	3	2	2	3	7	7	6	8	HC 500' fr W
4	4	4	4	2	1	1	1	4	2	9	5	HC at W. end
.07	.14	.17	.20	.17	.15	.10	.09	.16	.17	.12	.12	NOx at E. end
.10	.27	.23	.21	.18	.16	.16	.15	.30	.38	.30	.29	NOx 500' fr E
.19	.28	.12	.16	.13	.11	.23	.47	.55	.34	.50	.47	NOx at Center
.11	.20	.15	.08	.08	.08	.13	.32	.46	.32	.37	.29	NOx 500' fr W
.06	.07	.07	.07	.07	.07	.08	.10	.15	.11	.22	.22	NOx at W. end
												Particulates at center
												Traffic:
--	48	33	25	15	34	59	515	1027	863	629	620	Vehicles WB/hr.
--	31	24	21	23	15	20	60	133	189	283	402	Vehicles EB/hr.
--	79	57	46	38	49	79	575	1160	1052	912	1022	Vehicles Total
											0%	% Gas Trucks
											1%	% Diesel Trucks
												Speed:
--	47.4		34.1		40.9		39.4	45.9	43.4	42.4	36.2	Average WB
--	38.0		53.1		36.6		53.1	46.3	43.4	44.4	32.9	Average EB

Remarks: Supply Air at Midnite was CO = 0, HC = 4 and NO_x = .1

Supply Air was CO = 5 HC = 2, and NO_x = .12 when center CO = 75 at 7:00 AM

Date March 11, 1973 8941' Eisenhower Tunnel

TABLE II

Noon 12:00		2		4		6		8		10	Midnite 12	
29.87	29.87	29.87	29.87	29.87	29.88	29.88	29.89	29.89	29.90	29.91	29.91	Altimeter
19.87	19.97	19.97	19.97	19.98	19.98	19.98	19.98	19.99	19.99	19.99	20.00	E. Barometer
19.86	19.86	19.86	19.87	19.87	19.88	19.88	19.89	19.89	19.90	19.90	19.90	W. Barometer
					NW @ 25 mph							Wind at: 15,000' level
W5	SW2	SW	SW6	0	0	0	SW2	0	0			East end
E1	0	E1	0	0	W2	0	W2	0	0			500' fr E
0	0	0	0	W5	0	0	--	W5	0			Center
E3	W2	E1	0	W2	0	W1	W1	0	0			500' fr W
SW4	SW6	SW3	SW6	SW3	0	0	N3	0	0			West end
						13°F						Temperature at: 15,000' level
39	40	42	40	38	33	26	28	26	25			East end
43	45	46	48	47	47	41	43	42	43			500' fr E
46	46	47	48	49	49	49	--	--	--			Center
36	38	39	40	42	40	38	36	36	35			500' fr W
38	39	38	43	40	42	30	26	24	25			West end
24%		24%		24%		24%	--	--	--			Center Humidity
7 @ 100 hp →									4 @ 100 hp →			Supply Fans
6 @ 100 hp →									4 @ 100 hp →			Exhaust Fans
												Concentration
52	105	75	92	158	7	48	55	8	25			CO at E. end
145	114	105	150	125	85	37	52	48	30			CO 500' fr E
150	155	148	163	145	75	60	50	42	25			CO at center
112	128	123	175	190	147	70	72	55	43			CO 500' fr W
53	78	82	130	55	42	75	16	22	30			CO at W. end
7	12	9	14	19	2	8	8	3	5			HC at E. end
15	12	12	20	15	10	5	7	7	6			HC 500' fr E
15	14	16	17	15	10	7	7	6	5			HC at Center
10	15	26	22	17	13	7	10	7	6			HC 500' fr W
6	9	10	14	6	5	4	3	4	5			HC at W. end
.24	.37	.22	.27	.36	.13	.22	.30	.15	.17			NOx at E. end
.45	.52	.25	.40	.31	.46	.18	.27	.43	.21			NOx 500' fr E
.52	.68	.44	.46	.33	.42	.25	.27	.26	.21			NOx at Center
.58	.39	.31	.36	.40	.42	.24	.26	.32	.18			NOx 500' fr W
.30	.32	.21	.29	.20	.19	---	.13	.22	.16			NOx at W. end
						1915 $\mu g/M^3$						Particulates at center
												Traffic:
796	718	785	668	493	303	180	203	138	79			Vehicles WB/hr.
553	745	890	1167	1167	995	648	531	432	173			Vehicles EB/hr.
1349	1463	1675	1835	1660	1298	828	734	570	252			Vehicles Total
			1%									% Gas Trucks
			2%									% Diesel Trucks
												Speed:
26.5	30.3	36.3	35.3	34.8	34.5	40.3	39.7	39.0	40.2			Average WB
38.8	34.9	32.4	32.7	40.9	40.6	37.2	34.5	39.6	40.3			Average EB

Remarks: Fresh Air showed CO = 8, HC = 4, NO_x = .15 at 3:00 PM

From 4:00 PM until 6:00 PM Patrol encouraged traffic to use Loveland Pass

TABLE III

SUMMATION OF DATA FROM EISENHOWER TUNNEL
FOR FIRST 4 MONTHS OF OPERATION

Length = 8941 feet	Width = 34 feet
Height = 16.4 feet	Volume = Approx. 5,000,000 cu. ft.

During the first four months of operation there were:

4,357 fan hours at 12½ Horsepower = 125 rpm = 1/4 speed.
17,742 fan hours at 100 Horsepower = 250 rpm = 1/2 speed.
588 fan hours at 600 Horsepower = 500 rpm = Full speed.

A total of 177,000,000,000 cu. ft. of air was forced to 775,000 vehicles.
The average carbon monoxide concentration was 34 parts per million.
The carbon monoxide level exceeded 10 ppm, 84% of the time.
The carbon monoxide level exceeded 50 ppm, 24% of the time.
The carbon monoxide level exceeded 75 ppm, 5% of the time.
The carbon monoxide level exceeded 100 ppm, 0.3% of the time.

The CO level 500 ' inside the portals was approximately 80% of the value at the center.
The CO level at the portals was approximately 30% of the value at the center.
The total Hydrocarbon level was approximately 13% of the CO level.
The Nitrogen oxides level was approximately 0.4% of the CO level.
The Suspended particulates level averaged 2000 ug/M^3.
The temperature at the center of the tunnel averaged 50°F.

The cubic feet of air required in the tunnel could be reasonably well predicted by the formula:

$$CFM = \frac{97{,}000 \text{ (number of vehicles per hour)}}{\text{Desired concentration of CO in parts per million}}$$

and each supply fan produced an average of 125,000 cfm at 1/4 speed,
250,000 cfm at 1/2 speed
and 500,000 cfm at Full speed

NOTE: With this transverse system of ventilation, a corresponding exhaust fan should be run for every supply fan.

For the normal operation of the fans during the first 4 months of operation, the concentration of carbon monoxide could be predicted by the formula:

$$PPM_{co} = 13 + 0.05(VPH_{eastbound}) + 0.08(VPH_{westbound})$$

The highest hourly traffic volume was 1700 vph and the lowest was 20 vph.

The vph exceeded 100, 68% of the time.
The vph exceeded 500, 21% of the time.
The vph exceeded 1000, 2% of the time.
The vph exceeded 1500, .08% of the time.

September 1973

ANALYSIS OF DATA OTHER THAN WIND DATA

In view of the limits established for CO, HC and NO_x and presented on pages 8 and 9, the concentrations of these pollutants in the short tunnels was found to be very low. The average CO value for 160 readings in tunnels under 1000' long was 8.2 ppm; for hydrocarbons was 4 ppm and for NO_x was 0.17 ppm. The best correlation of concentration was with distance from the portal (0.300 correlation coefficient) and with outside wind velocity (-0.202). In general, the further from the tunnel entrance, the higher the concentrations; and the greater the wind velocity the smaller the pollution build-up inside the tunnel. The correlations might well be expected.

There is a fairly good correlation between CO concentration and hydrocarbon concentration (.344) and a very good correlation between CO concentration and NO_x (.722). The concentration of nitrogen oxides is approximately .015 times the concentration of CO.

For the 8941' long tunnel at 11,000 altitude the average CO value for 4 months of operation was 34 ppm; for hydrocarbons was 8 ppm, and for NO_x was 0.3 ppm. Temperatures and humidity values were low during the time that readings were taken in this long tunnel. No correlation of these values could be found with pollution values.

This long tunnel provided an opportunity for computer analysis of fan operation, CO concentration, traffic volume and emission data. Several of the relationships determined by regression analysis are shown on page 28 as SUMMATION OF DATA. From these formulas it is possible to provide efficient fan operation and to predict CO concentrations based on traffic volume. It was also possible to verify emission rates presented in other parts of this report.

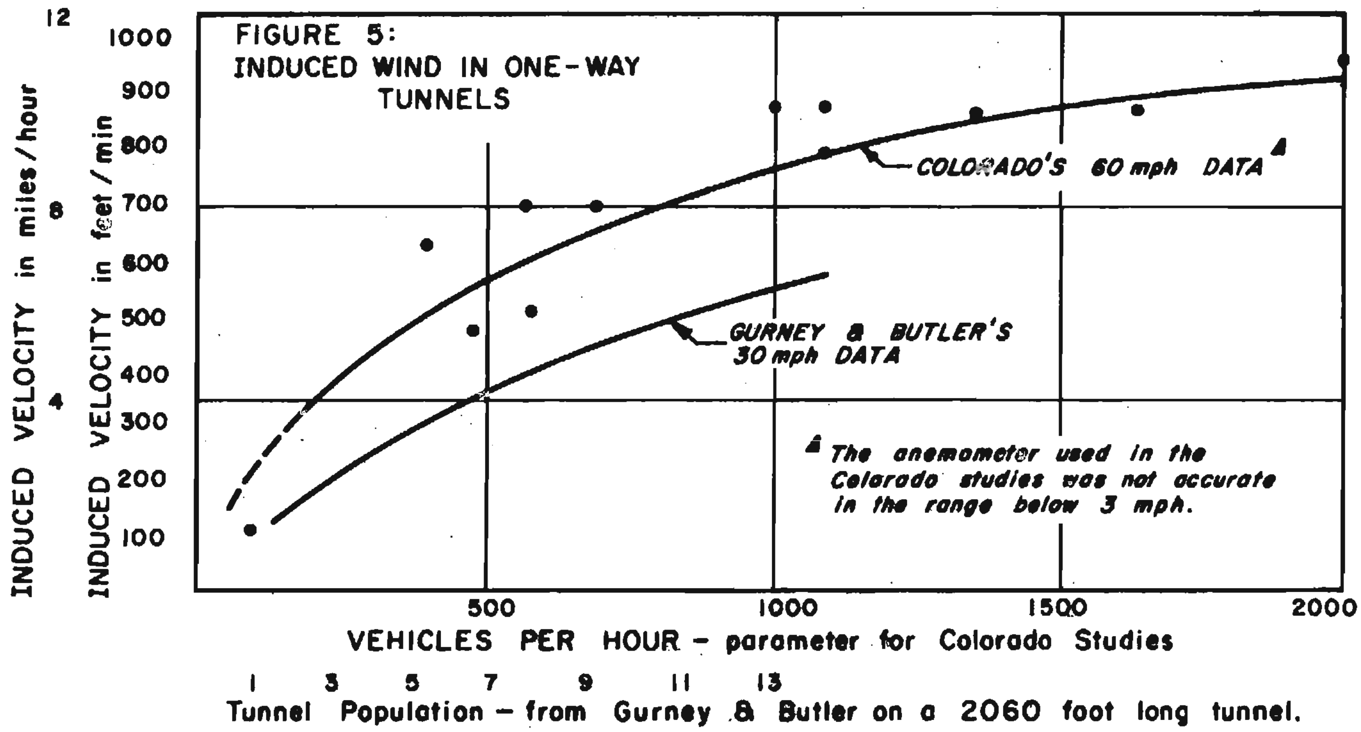
Samples, taken for this study, point out the tendency of CO to concentrate in pockets of tunnels where the lining is not straight and smooth. Several cavities in the Clear Creek Tunnels showed concentrations of 40 ppm while the average concentration out in the middle of the tunnel was only 10 ppm.

Analysis of Wind Data

An analysis of the wind data shows that the orientation of the tunnel and local topography do have a considerable effect on the induced draft, because inside wind speed does not correlate perfectly with traffic. However, the Clear Creek Tunnels are all two-way tunnels, and the wind inside the tunnel was about one-half the velocity of the outside wind, and always in the same general direction as the outside wind.

In short one-way tunnels, winds were generally induced inside the tunnels in some relationship to the amount of traffic. In fact, outside head winds of as much as 10 mph were occasionally overcome by strong, steady traffic when the topography was right. According to Mitani and Aisawa[(4)] 25% of the ventilation reqüired for tunnels over 3,300' in length will be supplied by natural ventilation. Gurney and Butler[(6)] provide additional information in their Equation No. 3. Sample calculations of a hypothetical situation are found on page 58.

Gurney and Butler's findings are compared to the findings from this study on the following graph:



Induced wind data for tunnels over 1000' long would appear to be valuable even though tunnel designers hesitate to use this information because they usually feel that it is not "wholly reliable." In an attempt to obtain some information on induced air flow, experiments were performed on the 8941' long tunnel at the 11,000' MSL elevation using 100 controlled cars to simulate one-way travel.

The natural air flow outside the tunnel (wind at the 11,000' elevation) is often from the northeast in the springtime as shown on the wind roses of Figure 6. On May 10, 1973 when the tests were performed, the wind was from the northeast at 10 to 15 miles per hour, and the midday temperature was 50°F. Inside the tunnel, however, the tendency was for a light wind from the west measured at approximately

2 mph inside the west portal, 5 mph at the center and 7 mph inside the east portal. This reversal of wind direction is not surprising because of the topography surrounding the tunnel area. See Figure 7. Winds along the Continental Divide are variable much of the time, and vortices constantly form and decay at both ends of the tunnel.

The 100 cars for the experiments were lined up 2-abreast and first sent through the tunnel westward at 40 mph. The velometer located 500' inside the east portal registered the west wind through the tunnel until the cars approached the sensor. After the lead cars passed the sensor (going westward) the wind began to blow from the east and gradually rose to 14 mph immediately after the last car had passed (130 seconds after the first car had passed and approximately 7100' behind the first car. Cars were spaced about 130' apart). Thereafter, the wind velocity (from the east) gradually reduced to zero during a period of 240 seconds, and the westerly wind began to blow again.

The sensor in the middle of the tunnel showed west winds at 5 mph when the first cars passed through the east portal. Thereafter, the winds from the west gradually died to zero in the 2 minutes that it took for the cars to reach the center. At that time, the winds became easterly and gradually rose to 9 mph 130 seconds later when the last car passed through the center of the tunnel. Thereafter the east wind gradually died to zero in 150 seconds and the wind started to blow from the west again.

The sensor 500' east of the west portal registered west winds at 2 mph when the first cars passed through the east portal. They remained at that direction and velocity for 2 minutes and 40 seconds when the first cars approached. They then switched to an easterly direction and gradually rose to 4 mph when about 1/2 the cars has passed. After that, the easterly winds gradually died to 1 mph when the last cars passed. Shortly thereafter the winds became westerly 1 to 2 mph.

The 100 test cars were then lined up 2-abreast headed eastward about a mile west of the west portal. The sensor 500' east of the west portal showed a 5 mph west wind as the first cars went by. It gradually increased to 12 mph as the last car went eastward. The west wind continued at about 12 mph for 3 minutes and gradually died down to 5 mph.

The sensor at the middle of the tunnel showed a west wind of about 5 mph as the first of the EB group of cars passed through the West portal. It gradually increased to 10 mph as the cars approached, and it continued to increase on up to 12 mph as the cars went by. Thereafter, it gradually decreased to 4 mph.

The sensor located 500' inside the east portal showed west winds of 7 mph gradually increasing to 14 mph as the cars from the west reached that location. The currents were westerly at about 14 mph until all the cars had passed (130 seconds for the 100 cars), afterwhich the velocity gradually diminished to 7 mph during the next 1 1/2 minutes.

On both test runs the induced wind appeared to average 7 mph for the 40 mph vehicle travel speed used.

The Gurney and Butler[6] Equation No. 3 applied to the conditions of these tests gives the following results:

$$\text{Induced Wind} = \left[\frac{\text{Speed of traffic}}{1+\sqrt{\text{Spacing}}\sqrt{\dfrac{(\text{End Loss Factor})(\text{X-Sec Area})+(\text{Wall Drag Coef})(\text{Perimeter})(\text{Tunnel Length})}{(\text{Vehicle Drag Coef})(\text{Vehicle Frontal Area})(\text{Tunnel Length})}}}\right]-C_1$$

$$= \left[\frac{40}{1+\sqrt{150'}\sqrt{\dfrac{(1)(574)+(.014)(103)(8941)}{(.5)\ (40)\ (8941)}}}\right]-C_1 = 9.3 \quad -C_1$$

Since the induced wind was found to be 7 mph for the 8941' long tunnel, the coefficient C_1 (not specified in the Gurney & Butler article) would appear to be approximately 2 mph. The loss in induced wind may be due to the 4' walkway and bannister on the south side of the tunnel.

It should be reported that the readings taken with the Alnor Velometers (Series 6000-P) for these tests showed quite erratic readings as the cars approached and passed by. This is annoying, of course, but not surprising in view of the different shapes and sizes of automobiles and the supply and exhaust vents which are built into the ceiling and curb lines. Even though the fans were off and the damper doors were closed, it was very possible that shock waves reverberated back and forth through the supply and exhaust ducts which compose over 4,000,000 cubic feet.

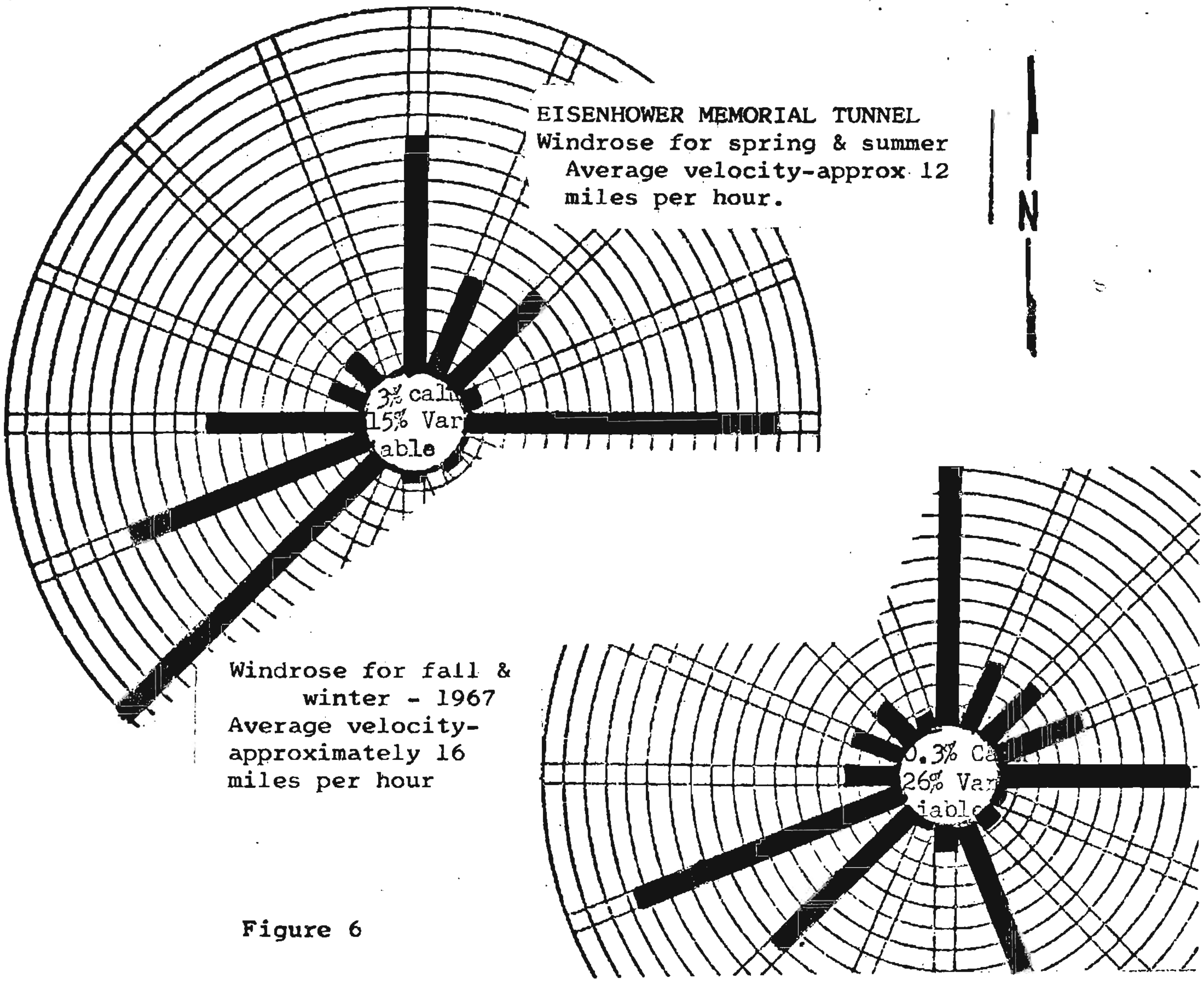


Figure 6

WIND FREQUENCY DISTRIBUTION - D STABILITY CLASS, 65% Most Probable
March and April 1973

Direction	0-3 mph	4-8 mph	8-12 mph	13-18 mph	Total	% Total
N	57	47	25	3	132	10.0
NNE	26	15	28	4	73	5.6
NE	16	14	49	9	88	6.7
ENE	1	4	6	1	12	.9
E	23	78	57	35	193	14.9
ESE	1	1	0	0	2	.1
SE	3	5	1	0	9	.7
SSE	0	1	0	0	1	0
S	2	2	1	0	5	.4
SSW	0	0	0	0	0	0
SW	53	79	50	50	232	17.8
WSW	29	66	44	25	164	12.5
W	18	35	22	24	99	7.6
WNW	0	4	2	10	16	1.2
NW	10	16	7	0	33	2.5
NNW	0	3	0	0	3	.2
CALM	45	0	0	0	45	3.4
VARIABLE	74	91	36	0	201	15.5

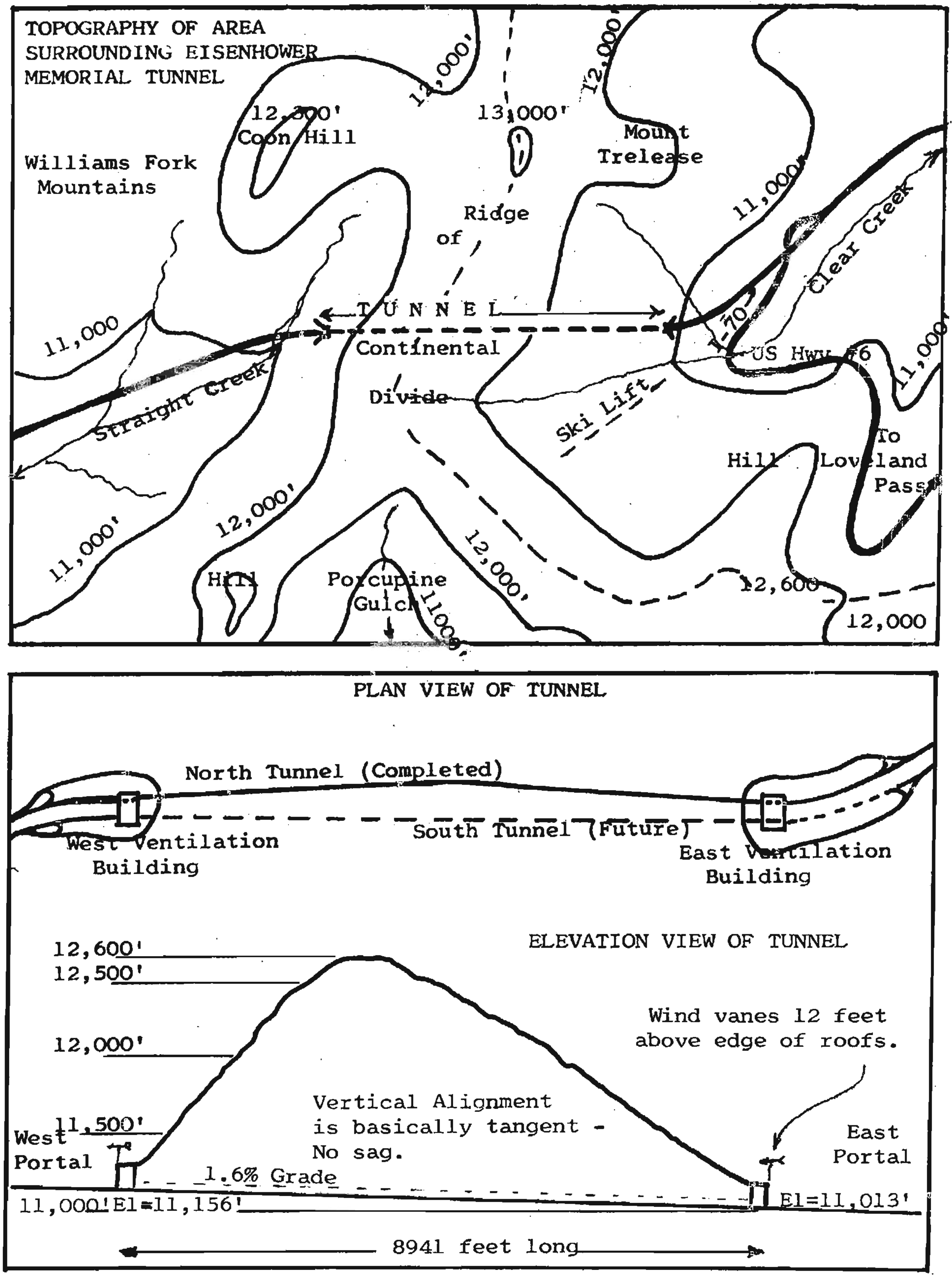

TOPOGRAPHY OF AREA
SURROUNDING EISENHOWER
MEMORIAL TUNNEL
12,300'
Coon Hill
13,000'
Mount
Trelease
Williams Fork
Mountains
Ridge
of
11,000
12,000'
T U N N E L
Continental
Divide
I-70
US Hwy 6
Clear Creek
Straight Creek
Ski Lift
To
Loveland
Pass
Hill
12,000'
11,000'
Hill
Porcupine
Gulch
12,000'
12,600
12,000
PLAN VIEW OF TUNNEL
North Tunnel (Completed)
South Tunnel (Future)
West Ventilation
Building
East Ventilation
Building
ELEVATION VIEW OF TUNNEL
12,600'
12,500'
12,000'
11,500'
Wind vanes 12 feet
above edge of roofs.
Vertical Alignment
is basically tangent -
No sag.
West
Portal
East
Portal
1.6% Grade
11,000' El=11,156'
El=11,013'
8941 feet long

Figure 7

COMPUTED CONCENTRATION VALUES

An attempt was made to compute the concentrations of pollutants for this tunnel study using the California mixing cell theory, the Mining Safety Appliance Research Corporation formula and formulas based on the conservation of mass.

Personnel in the California Division of Highways have developed a procedure for computing the horizontal concentration of gases based on the dispersion of this gas from an idealized MIXING CELL. This mixing cell is defined as the chamber where there is an intense zone of mixing and turbulence caused by the motion of vehicles. Tests with smoke candles have indicated that the roof of the chamber in open air is about twice the vehicle's height, and for convenience the width is taken as the width of the pavement (approximately 35 feet). The length of the line of vehicles under consideration determines the extent of the chamber, since the emission from these vehicles constitutes a "line" source of pollutants.

In an unventilated tunnel, the gases would be confined by the sides (which are about 35' apart) and the roof (which is about 15' high) so that in effect there is a mixing cell from the open air, continuing through the tunnel, and then reverting back to open air on the other side of the tunnel. Of course, the concentration in the mixing cell is lowered by wind and turbulence in the unconfined atmosphere, whereas, the concentration builds up inside the tunnel. It should be possible to calculate the concentration of the mixing cell both inside and outside the tunnel and draw isolines of concentration for given conditions of wind and vehicular emission using the California formula:

$$\text{Concentration} = K' \frac{1.060 \text{ (Emission source strength in gr/mi per sec)}}{\text{(Wind speed in meters per sec)(Sine of the angle of the wind to longitudinal axis of the roadway)}}$$

A sketch showing the results of computations with this formula for the build-up of CO in the Stapleton Field Tunnel is shown on Figure 8.

FIGURE 8 CALCULATIONS USING THE CALIFORNIA MIXING CELL FORMULA FOR CARBON MONOXIDE CONCENTRATION IN THE TUNNEL AT STAPLETON FIELD NEAR DENVER, COLORADO (Tunnel has 8 fans which have never been used)

The concentration of CO within the mechanical mixing cell is: $C = \frac{1.06\ Q}{K\ U\ (\sin \phi)}$

where Q = source strength = 1.73×10^{-7} X vehicles/hr X emission in gr/mile.

K = California constant of correlation = 4.25 1/K=K' from formula on p. 38.

U = wind speed in meters/second, and ϕ = angle of wind to highway ℄.

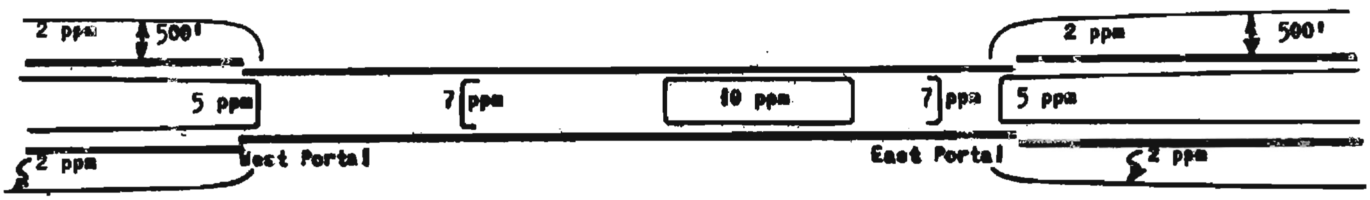
For Stapleton Field Tunnel at usual daytime conditions of WSW wind 8mph and 2000 vehicles/hr: $Q = 1.73 \times 10^{-7} \times 2000 \times 50 = 0.0173$ gr/sec/meter, and

$$C = \frac{1.06(0.0173)}{4.25(3.6)\ 0.375} = 0.0183/5.74 = 0.00319\ gm/m^3 = 2.8\ ppm$$

From the California correlation curves on dispersion in the corridor outside the tunnel:

Distance from Highway	C U K/Q	C	ppm	Back-ground	Total CO
0 feet	-	0.00319	3	2	5 ppm
50	1.25	0.00141	1.23	2	3 ppm
100	.85	0.00096	0.84	2	3 ppm
500	.34	0.00038	0.33	2	2 ppm

So isolines of CO concentration for the Stapleton Field Tunnel are typically as shown for the WB lane when wind = 8 mph ↗ Westbound traffic ←



PLAN VIEW based on computations using the California formulas and typical readings of CO concentration inside the tunnel.

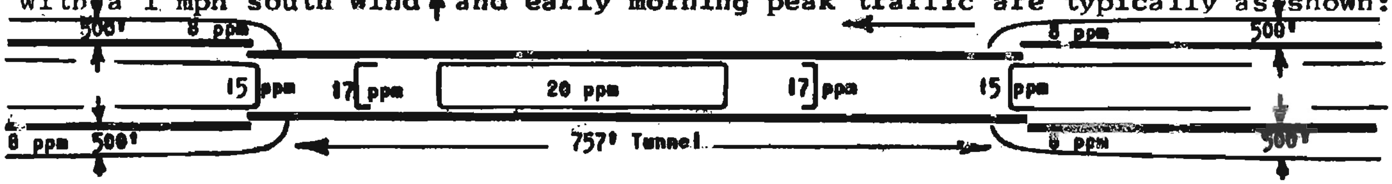
For usual morning condition where peak traffic is 3000 vehicles/hr and wind is 1 mph from the south:

$C = \frac{1.06\ Q}{K\ U(\sin \phi)}$ where $Q = 1.73 \times 10^{-7} \times 3000 \times 50 = 0.026$.

$C \doteq \frac{1.06\ (.026)}{4.25 \times .45 \times 1} = 0.0144\ gr/m^3$. Then using California curves for early morning stable conditions and $\phi = 90^{\circ}$:

Distance from Highway	C U K/Q	C	ppm	Back-ground	Total CO
0 feet	-	0.0144	12.6	2	15
50	0.7	0.0095	8.3	2	10
100	0.6	0.0082	7.1	2	9
500	0.44	0.0060	5.2	2	8
1000	0.39	0.0053	4.6	2	7

Isolines of CO concentration for the WB lane through Stapleton Field Tunnel with a 1 mph south wind ↑ and early morning peak traffic are typically as shown:



Use of the MSA Formula

A linear differential equation was obtained by MSA to calculate the profile of pollutant concentration thru the length of a tunnel. (See Equation (8) in Report No. FHWA-RD-72-15). Using the following assumptions in tunnel ventilation theory:

a. There is no appreciable removal of oxygen, nor production of CO_2, nor water vapor,

b. the gas composition is uniform across the cross section of the tunnel,

c. longitudinal diffusion is negligible,

a mass balance differential equation was obtained. The Mine Safety Appliance Research Corporation developed a program that processed a numerical solution. This program can take into account varying lateral and longitudinal ventilation.

This equation was integrated and the terms adjusted for conditions existing in the Eisenhower Memorial Tunnel, to obtain the following equation for pollutants inside a tunnel:

$$C = C_o + \frac{G}{Q}\left(1 - \exp\frac{-QX}{AV}\right) \qquad (1)$$

where:

C = Pollutant Concentration inside a tunnel.

C_o = Ambient Pollutant Concentration.

G = Rate of Pollutant Emission

Q = Cross Ventilation inside the tunnel.

X = Distance from the tunnel portal.

A = Tunnel cross section area.

V = Axial wind velocity inside tunnel.

This equation may be used when a linear build-up of pollutants exist inside the tunnel and uniform power ventilation is present. Figure 9 shows results of this equation applied to Eisenhower Memorial Tunnel for various conditions of wind inside the tunnel and number of supply fans running at full speed which is 500 rpm and 600 hp each. (The total number of fans running is double the numbers shown since the tunnel has transverse ventilation and there is an exhaust fan for each supply fan used.) Figure 10 shows the actual concentrations observed in this tunnel. Actual concentrations are somewhat greater than the computed ones using the theoretical output of the fans. This is a common occurrence in almost all tunnels. The loss in efficiency is believed to be due to friction in the vents which reduces the actual amount of air actually supplied to the tunnel.

When no power ventilation exists, the preceding equation reduces to:

$$C = C_o + \frac{GX}{AV} \qquad (2)$$

or by consolidating conversion constants:

$$C = C_o + \frac{0.0011(\text{veh per hour})(\text{gr per mi per vehicle})(\text{feet from portal})}{(\text{tunnel crossec area in ft}^2)\ (\text{wind speed in mph})}$$

An empirical term, $\xi(X)$, was added to equation (2) to take into account the lateral diffusion of pollutants and other terms neglected in the MSA equation.

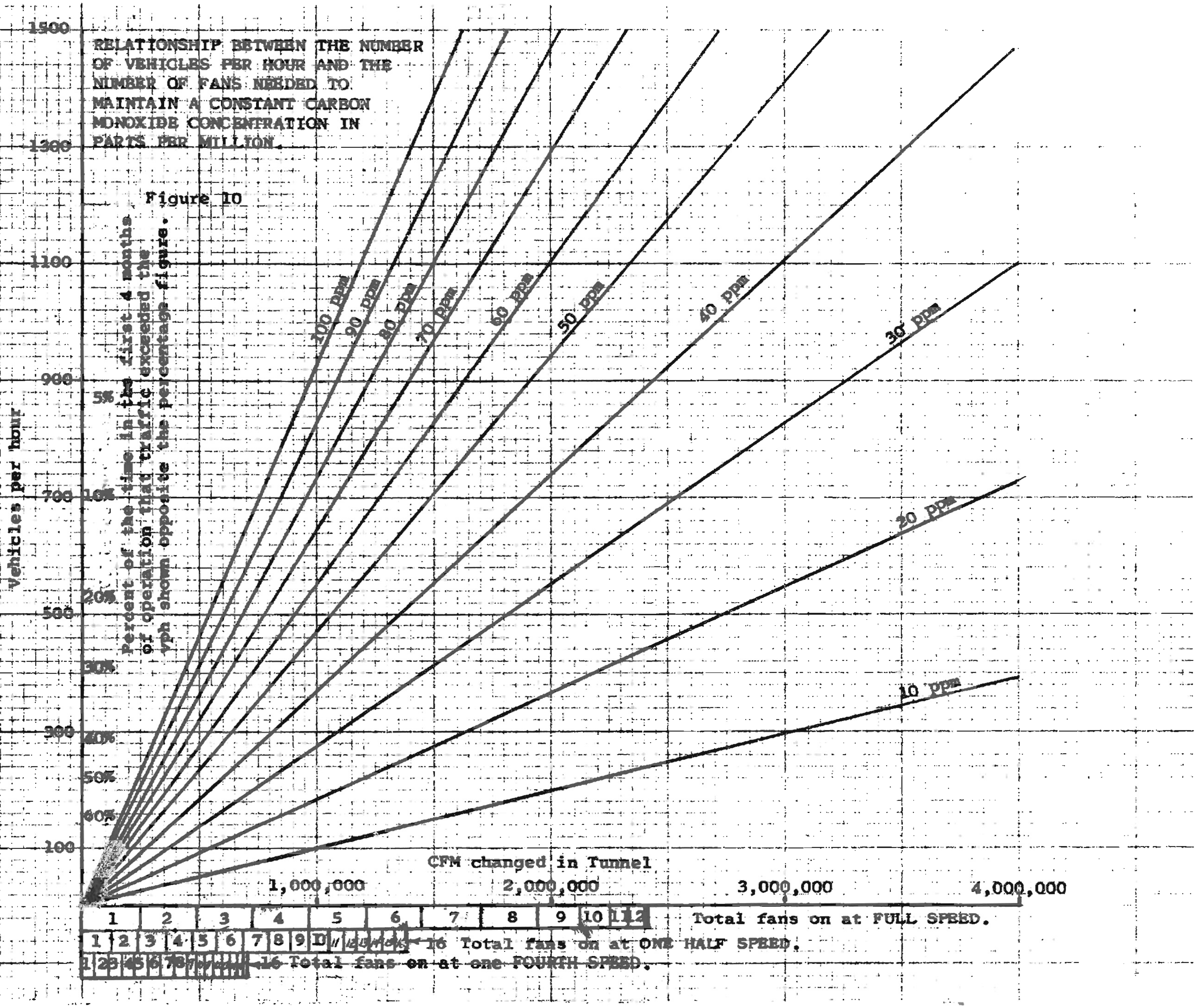
In order to find the functional form of $\xi(X)$, it was necessary to take five samples simultaneously at several distances through the tunnel keeping the remainder of the variables besides C and X constant.

To obtain the five simultaneous readings, four tunnel sites were selected and the instrumentation was set up to measure the concentration of carbon monoxide and hydrocarbons in each tunnel with five different sampling devices. The five sampling devices were positioned approximately 150 feet apart and a five minute air sample was collected simultaneously in each. A 15-minute traffic count taken during and preceding the air

FIGURE 9

CARBON MONOXIDE CONCENTRATION AT VARIOUS LOCATIONS
THROUGH STRAIGHT CREEK TUNNEL BASED ON THE MSA FORMULA

Grade	Wind	Fans	Traffic	Distance from Upwind Portal 500'	1000'	2000'	3000'	4000'	5000'	6000'	7000'	8000'	8941'
Up 1.64% Grade	Wind 15 mph	8 Fans	500 veh/hr	3	5	8	10	11	11	11	11	11	11
			1500 veh/hr	9	16	25	29	32	33	33	34	34	34
		4 Fans	500 veh/hr	3	6	11	14	16	18	19	20	21	22
			1500 veh/hr	10	19	32	42	49	55	58	61	63	65
		1 Fan	500 veh/hr	4	7	13	19	25	30	35	39	43	47
			1500 veh/hr	11	21	40	58	75	90	104	117	129	141
	Wind 5 mph	8 Fans	500 veh/hr	7	10	11	11	11	11	11	11	11	11
			1500 veh/hr	21	29	33	34	34	34	34	34	34	34
		4 Fans	500 veh/hr	9	14	19	21	22	23	23	23	23	23
			1500 veh/hr	26	42	58	64	67	68	68	68	68	68
		1 Fan	500 veh/hr	10	19	35	47	56	64	69	74	78	80
			1500 veh/hr	31	58	104	140	168	191	208	222	233	243
Down 1.64% Grade	Wind 15 mph	8 Fans	500 veh/hr	1	3	4	4	4	4	4	5	5	5
			1500 veh/hr	4	6	10	12	13	13	13	14	14	14
		4 Fans	500 veh/hr	1	2	4	6	7	7	8	8	8	9
			1500 veh/hr	4	7	13	17	20	22	23	24	25	26
		1 Fan	500 veh/hr	1	3	5	8	10	12	14	16	17	18
			1500 veh/hr	4	8	16	23	30	36	42	47	52	56
	Wind 5 mph	8 Fans	500 veh/hr	3	4	4	5	5	5	5	5	5	5
			1500 veh/hr	8	12	13	14	14	14	14	14	14	14
		4 Fans	500 veh/hr	3	6	8	9	9	9	9	9	9	9
			1500 veh/hr	10	17	23	26	27	27	27	27	27	27
		1 Fan	500 veh/hr	4	8	14	19	22	25	28	30	31	32
			1500 veh/hr	12	23	42	56	67	76	83	89	93	97
50% Up 1.64% Grade 50% Down 1.64% Grade	Wind 0 mph	8 Fans	500 veh/hr	8	8	8	8	8	8	8	8	8	8
			1500 veh/hr	23	23	23	23	23	23	23	23	23	23
		4 Fans	500 veh/hr	15	15	15	15	15	15	15	15	15	15
			1500 veh/hr	46	46	46	46	46	46	46	46	46	46
		1 Fan	500 veh/hr	62	62	62	62	62	62	62	62	62	62
			1500 veh/hr	186	186	186	186	186	186	186	186	186	186
	Wind 5 mph	8 Fans	500 veh/hr	5	7	7	8	8	8	8	8	8	8
			1500 veh/hr	14	20	23	24	24	24	24	24	24	24
		4 Fans	500 veh/hr	6	10	13	15	15	16	16	16	16	16
			1500 veh/hr	18	29	40	45	52	52	52	52	52	52
		1 Fan	500 veh/hr	7	13	24	33	39	44	48	52	54	56
			1500 veh/hr	21	40	73	98	117	133	146	155	163	170



RELATIONSHIP BETWEEN THE NUMBER OF VEHICLES PER HOUR AND THE NUMBER OF FANS NEEDED TO MAINTAIN A CONSTANT CARBON MONOXIDE CONCENTRATION IN PARTS PER MILLION.

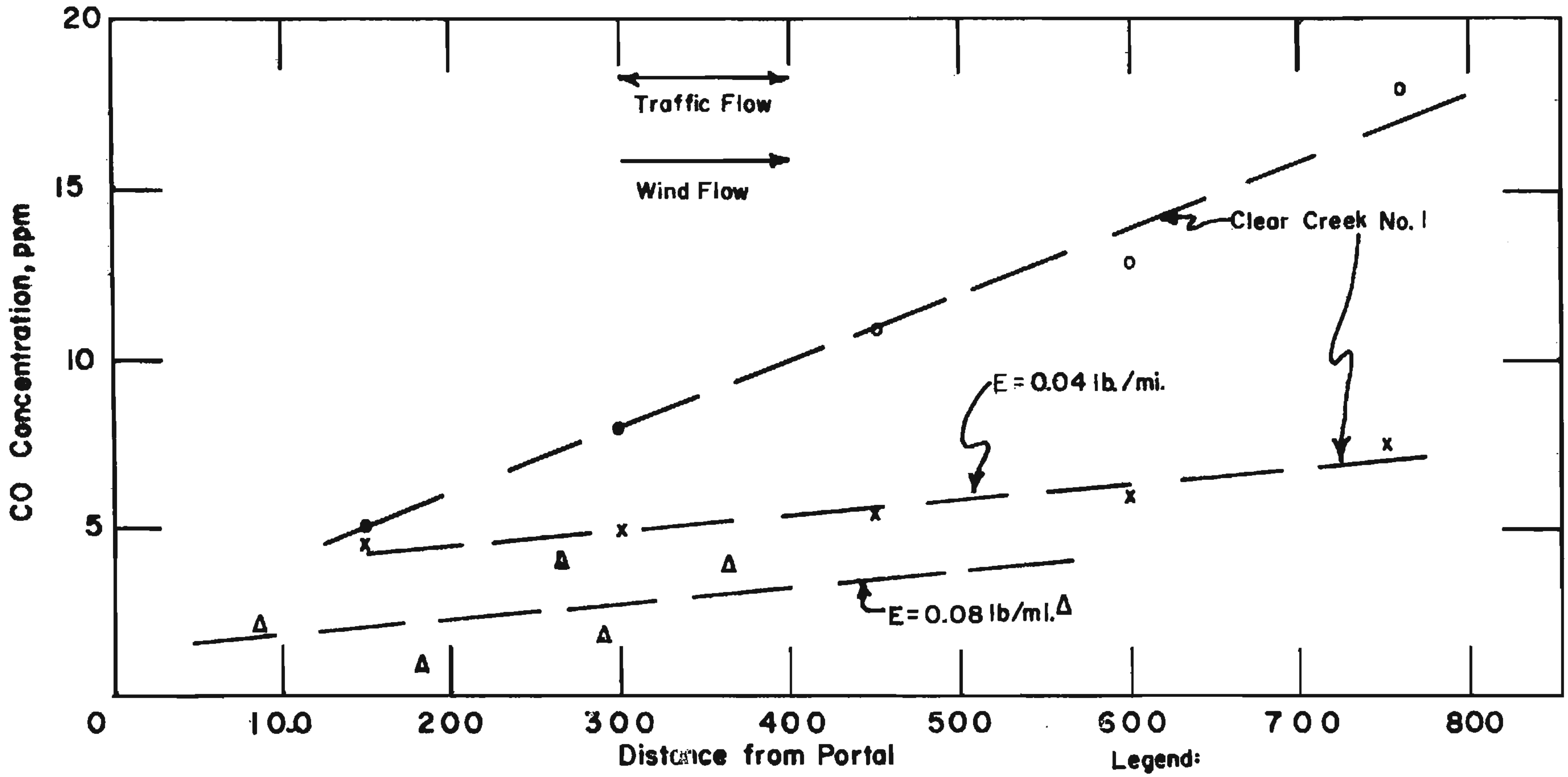
Figure 10

sampling was used to determine traffic volumes, classification and average speeds. Meteorological information was obtained inside and outside the tunnel. Even though air velocity was measured, it was not used since the instrument used was not very reliable at low velocities. These tests were taken twice in each of the six tunnels at the four sites. Results of these tests are included on pages 45 through 47.

Preliminary results indicate that $\lesssim(X)$ is zero and C is a linear function of distance. This is especially true when the natural wind dominates the traffic in two-way tunnels and the wind does not null the piston effect in one-way tunnels. This fact is illustrated in Figures 11, 12, and 13 which show profiles of CO concentration found in the seven tunnels measured using five simultaneous readings. (A positive value for the outside wind velocity indicates that the wind was in the direction of the distance scale.) The graphs illustrate the linear build-up of contaminants in the direction of the wind in the two-way tunnels and in the direction of the traffic (and wind) in one-way tunnels. Generally, in two-way tunnels, the pollution is greatest at the downwind portal. In one-way tunnels, with moderate to heavy traffic, the pollution build-up increases in the direction of traffic.

The graph from the Idaho Springs Westbound Tunnel results show the effect of the traffic flow acting against the outside wind flow. For the first 200 feet from the portal the traffic piston effect pushes the contaminants in a westerly direction. From that point on, the wind flow overcomes the piston effect resulting in a maximum build-up of

TYPICAL
PROFILE OF CO CONCENTRATION
WITH CONSTANT CONDITIONS
IN TWO WAY TUNNELS
FIGURE 11

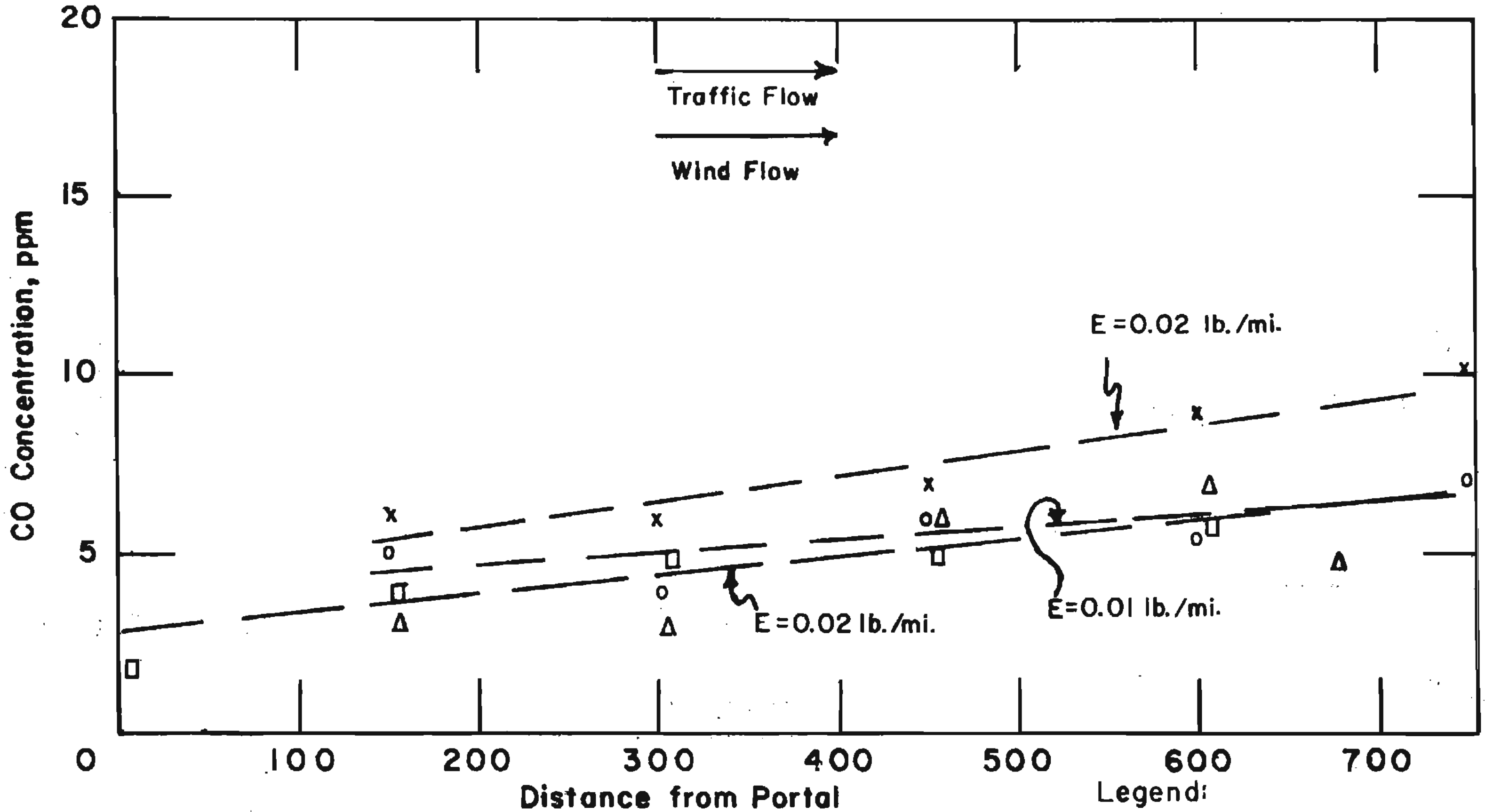


Note: Line location computed from points determined from field measurements.

Legend:

	Tunnel	Length	Veh/hr	Wind
o	Clear Creek I	859	222	0
x	Clear Creek I	859	284	2
Δ	Clear Creek 6	588	154	2

TYPICAL
PROFILE OF CO CONCENTRATION
WITH CONSTANT CONDITIONS
IN ONE WAY TUNNELS
FIGURE 12

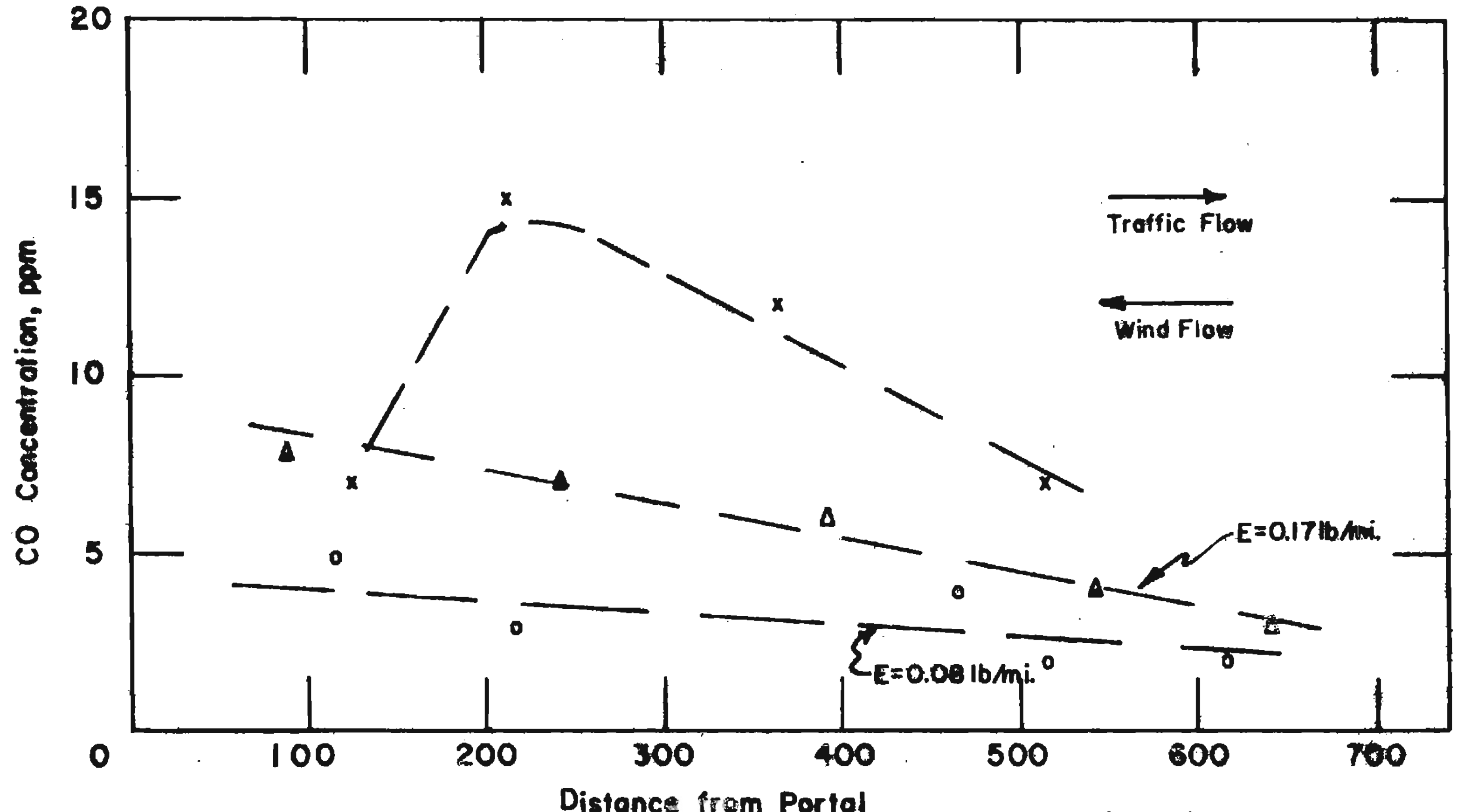


Legend:

	Tunnel	Length	Veh/hr	Wind
x	Stap-EB	757	1514	4
o	Stap-EB	757	1656	2
Δ	Stap-WB	757	769	0
□	Stap-WB	757	996	2

Note: Line location computed from points determined from field measurements.

PROFILE OF CO CONCENTRATION
WITH CONSTANT CONDITIONS
TUNNEL: IDAHO SPRINGS-WB
FIGURE 13



Note: Line location computed from points determined from field measurements.

Legend:

	Veh/hr	Wind
o	223	-4
x	212	-1
Δ	226	-3

contaminants inside the tunnel. This curve also shows that a 1 mph outside wind velocity has greater influence than 212 vehicles per hour since the maximum point on the curve is to the left of the tunnel center.

In conditions where an outside wind exists, the emission rate per vehicle (E) is indicated on the graphs. The average rate was found using equation (2) to be between .02 to .08 lbs/mi which agrees closely with the results of the auto emission tests.

Based on the results of the concentration profile study, and the series of five simultaneous readings, the linear model of CO build-up inside a tunnel applies to most tunnels in Colorado. It should be noted, however, that the experimental data is limited to traffic volumes below 2,500 veh/hr and tunnels less than 1070 feet long.

Computations were also made for carbon monoxide concentration build-up during IDLE conditions, because of the need for such information in case of an accident and traffic slow down. Experiments to check these computations were performed in conjunction with the 100 car tests previously described on pages 32 and 33. Table IV is a summary of the data obtained by arranging 100 cars in the tunnel to simulate a stopped vehicle condition with different fan operation settings.

The concentrations of CO obtained at the sensors in the 5 pulpits did not agree entirely with the concentrations shown by the sensors in the exhaust ducts or by the analyzer in the roving van. However, the average CO concentrations at equilibrium conditions present a good indication of the conditions in the tunnel with the fan settings shown.

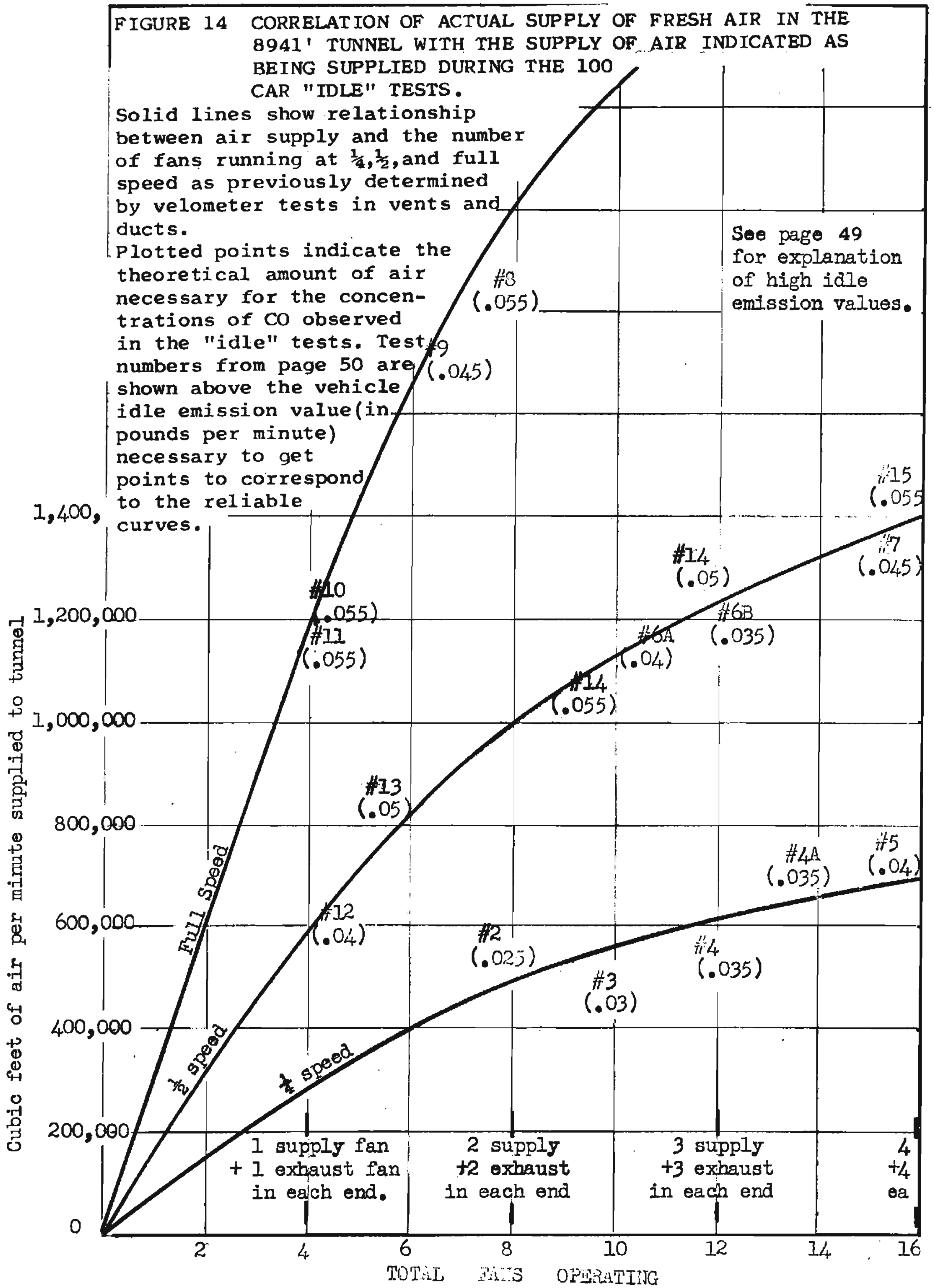
The computed concentrations were based on 4 reasonable values for average idle emission. In 1964, the average emission for the 40 car tests was .05 #/minute. In the 1973 tests the value was near 0.02 #/minute. The output of fresh air by the fans was based on average values of air measured from the outputs of the 1340 fresh air vents and the 508 exhaust air vents.

It appears that there was considerable carburetor loading as the tests progressed. For instance, for the first few tests, the actual values appear to conform generally to idle emission rates of 0.02 to 0.03 #/minute. As the cars remained in place and idled longer, the concentrations agree more with the computations based on the 0.03 to 0.04 #/minute emissions, and finally after some 2 or 3 hours of idling, the concentrations agree more with computations based on the 0.04 to 0.05 #/minute emission rate. See Figure 14 and Table IV. Tests were run during September of 1973 on vehicles built prior to 1969 and on vehicles with controlled emission built after 1969. The results showed that carburetor time-loading-increase is typical of older model vehicles and results in a maximum of about 150% of the early idle emission rate. It is apparently associated with heating of the engine and the air taken in the carburetor. Late model engines are built to operate at high temperatures and the increase in CO emission after long periods of IDLE is not as noticeable for post 1970 models.

TABLE IV

SUMMARY OF DATA ON 100 CAR TEST SERIES
(1/4 = fans at 1/4 speed, 1/2 = 1/2 speed and F = Full Speed.)

Test No.	Speed & Number of SUPPLY FANS In Each End 1	2	3	4	Speed & Number of EXHAUST FANS In Each End 1	2	3	4	Average CO Concentration at Equilibrium Conditions: Pulpits	Exhaust Ducts	For 100 cars idling in the Tunnel — Computed Concentrations For Various Idle Emissions Pounds CO per Minute: .02	.03	.04	.05
1	¼	¼	-	-	¼	¼	-	-	10 ppm	10 ppm	Conditions just before tests were started.			
Cars at 75' Spacing														
2	¼	¼	-	-	¼	¼	-	-	106	97	75	112	147	183
3	¼	¼	¼	-	¼	¼	-	-	107	107	65	100	130	163
4	¼	¼	¼	¼	¼	¼	-	-	100	112	60	92	120	149
4A	¼	¼	¼	¼	¼	¼	¼	-	104	102	55	85	112	138
5	¼	¼	¼	¼	¼	¼	¼	¼	101	102	53	80	105	130
6A	-	¼	¼	¼	½	½	½	½	64	98	31	47	64	80
Cars Moved to 25' Spacing														
6B	¼	¼	¼	¼	½	½	½	½	49	70	30	46	61	77
7	½	½	½	½	½	½	½	½	63	70	27	42	57	72
8	F	F	-	-	½	½	½	½	64	65	20	28	37	46
9	F	-	-	-	½	½	½	½	47	64	27	34	43	55
10	F	-	-	-	F	-	-	-	95	87	30	46	61	77
Cars Moved to 50' Spacing														
11	F				F				99	95	30	46	61	77
12		½				½			140	112	60	93	122	153
13	½	½				½			112	122	45	67	90	112
14	½	½	½	½		½			98	100	33	50	67	83
14A	½	½	½	½	½	½			80	85	30	46	61	77
15	½	½	½	½	½	½	½	½	80	75	27	42	57	72



September 1973

AUTOMOBILE EMISSION DETERMINATIONS

Equations for the build-up in concentration of pollutants depend upon the accurate determination of emission rates. Considerable research has been undertaken to obtain reliable values, and the results have been reported by the Mine Safety Appliances Corporation, Environmental Protective Agency and other agencies. The latest Environmental Protective Agency values are presented as Table 2 on the following page.

In 1964, TAMS Consulting Firm, the Taft Health Center and the Colorado Department of Highways undertook a project to determine CO emission at high altitudes to aid in the design of Eisenhower Memorial Tunnel. Emission rates of 40 representative cars were measured at different speeds, grades, and altitudes above 5,000 feet. The average emission rate for the 40 cars operating above 5,000 feet (the formulas are <u>not</u> good below the 5,000' elevation) in 1964-65 may be expressed for 50 mph in grams/mi by the formula:

$$CO_{1964} = -13.4 + 11h + (4.6h-18.5)\,G + (.34h + .4)\,G^2 - (.1h - .9)G^3 - (.013h - .078)G^4$$

where h = elevation in thousands of feet and G = the grade expressed in percent.

Soon after the 40 "average cars" were tested, Engineers at the Stevens Institute of Technology performed tests at simulated altitudes in the laboratory in connection with the same design problem. Their work included tests at sea level as well as above 5,000', and a formula which expresses CO emission to a reasonable degree between sea level and 11,000', and between -2% and +4% grade is:

$$CO = \frac{1500}{mph} + \frac{H}{316} + \frac{H - 6000}{170} + \frac{H + 2000}{4000}\,G^3$$

where H = elevation in feet above sea level.

TABLE V

EMISSION FACTORS FOR GASOLINE-POWERED MOTOR VEHICLES[a]

Emissions, g/mi	1960	1965	1970	1971	1972	1973	1974	1975
Carbon Monoxide								
Urban @ 25 mph	120	120	95	90	85	80	75	60
Rural @ 45 mph	70	70	60	55	50	45	40	35
Hydrocarbons								
Evaporation	2.7	2.7	2.7	2.3	2.3	1.8	1.8	1.4
Crankcase	4.1	2.7	0.9	0.45	0.45	0.32	0.22	0.22
Exhausts								
Urban	16	16	12	11	9.5	8.5	7.2	6
Rural	10.5	10.5	8	7	6.5	6	5	4
Nitrogen Oxides (NO_x as NO_2)	6.58	6.60	6.63	6.47	6.17	5.75	5.55	4.90
Particulates	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1
Sulfur Oxides (SO_2)	0.18							
Aldehydes (HCHO)	0.36							
Organic Acids (acetic)	0.13							

No legislation is in effect or has been proposed for these pollutants, and thus only one factor is presented.

a. SOURCE: U. S. Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors, February 1972."

In 1972, five cars having displacements of 440, 304, 250, 95 and 70 cubic inches were tested at the same high altitude sites. The cars were relatively new with low mileage, and there is no contention that their average emission represents the average emission which would be found on roadways today. Nevertheless, the equation representing the average emission at elevations above 5000' at 50 mph was:

$$CO_{1972} = -30.4 + 9.6h + (2.1h - 4.6)G + (-.27h + 4.2)G^2 + (-.04h + .54)G^3$$

A comparison of the 1964 emission rates compared to the rates found with 1972 model cars is shown on Figure 15. The new 1972 models put out about 25% less CO at 0% grade and about 40% less at +2% grade. Colorado does not require the blower that is used in California to meet the emission limitations, so most cars are not equipped with them. Only the Datsun and Mazda had blowers. The other three cars had only crankcase blowby control and arrangement to prevent advance timing at low speed. Being new cars, they had relatively good carburization and combustion.

The new 1972 model cars tested did show an improvement in pollution control at IDLE. In 1964, the average emission was 23 grams/minute. For the 1972 cars, the average idle emission was 7 grams/minute. This improvement, and the reduction of CO due to the use of new, low mileage cars, accounts for most of the reduction in the carbon monoxide noted in the 1972 tests.

In March 1973, forty-three vehicles again selected to represent a proper proportion of sizes, makes and ages were instrumented and driven

THROUGH the completed westbound bore of the 1.7 mile Eisenhower Tunnel. The purpose was to determine as near as possible the actual carbon monoxide emission rate at the 11,000' altitude for grades of 1.64% uphill and 1.64% downhill. The results gave the average of 94.3 gr/mile uphill and 47.2 gr/mile downhill shown on Figure 15.

The data all seems to indicate that there is a gradual reduction in carbon monoxide emission on later model cars. However, the average CO emission on a level grade at 11,000' altitude is approximately 69 gr/mile, or about 1 1/2 times the average emission factor published by EPA for rural travel at 45 mph. The average emission for idle at 11,000' was 0.02 #/minute = 9 grams per minute.

The 100 car experiments, previously described on pages 32 and 33, provided an excellent opportunity to check vehicle emission rate during idling and during smooth traffic flow. The results of the tests on the 100 vehicles idling in the 8941' tunnel were described on page 48.

The results of the 100 car tests during the One-way Piston Effect Runs (see pages 32 and 33) showed an average of 100 grams/mile up the 1.64% grade (WB), and 55 gr/mile down the 1.64% grade. (A reproduction of the graphs on the 7 analyzers is shown as Figure 16.) These figures agree quite well with the overall values for emission obtained from 4 months of average fan output, tunnel concentration and vehicle per hour data analyzed to show 120 gr/mile uphill and 60 gr/mile downhill. Both of these sets of emission figures are larger than the 94.3 gr/mi and 47.2 gr/mi determined by actual individual vehicle tests, but this might be expected since the data from which the two previous sets of emission values were derived was taken from analyzer graphs, somewhat uncertain fan settings, data occasionally containing high truck percentages, and often, very low traffic volumes.

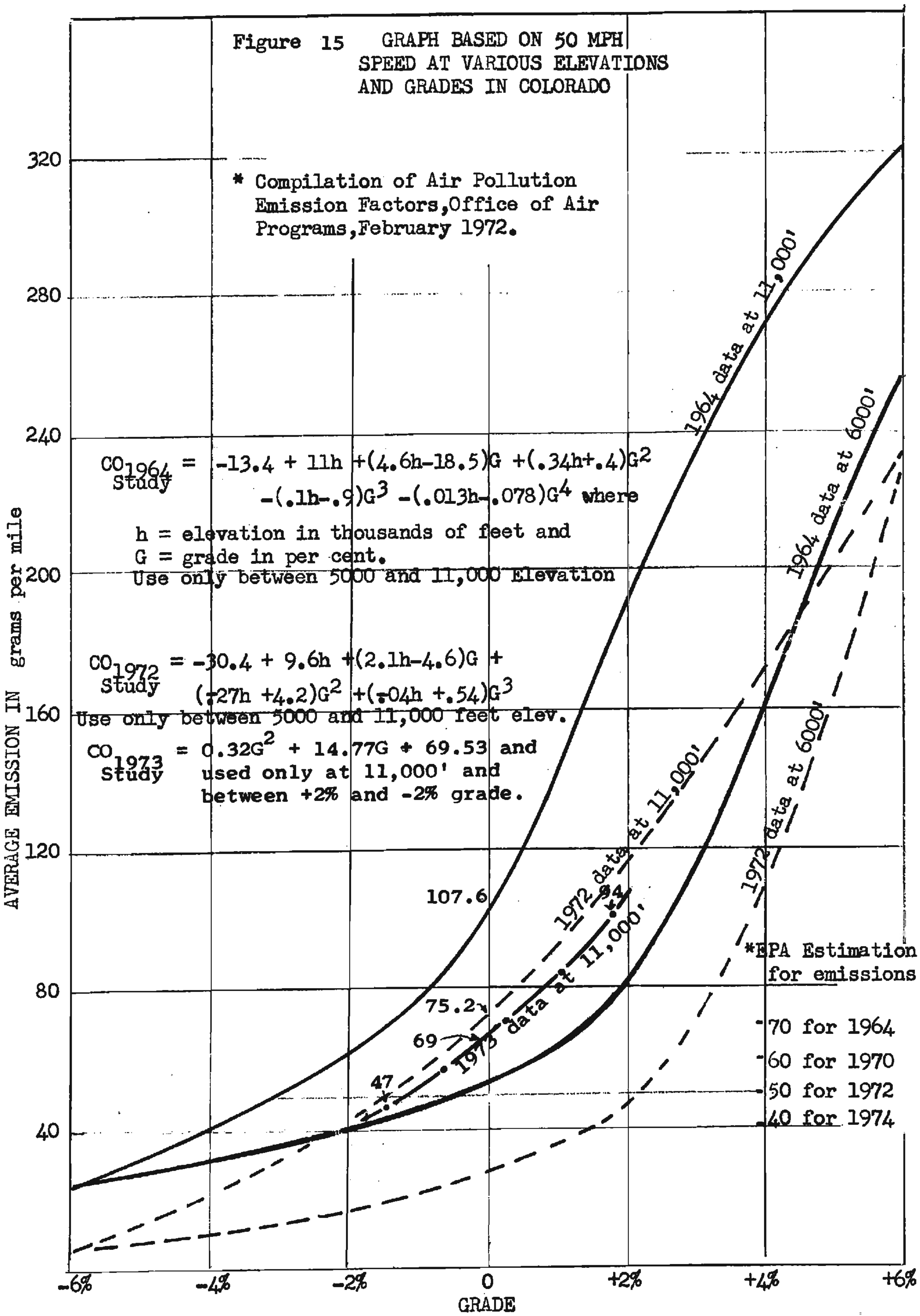


Figure 15 GRAPH BASED ON 50 MPH SPEED AT VARIOUS ELEVATIONS AND GRADES IN COLORADO
* Compilation of Air Pollution Emission Factors, Office of Air Programs, February 1972.
CO 1964 Study = -13.4 + 11h +(4.6h-18.5)G +(.34h+.4)G2 -(.1h-.9)G3 -(.013h-.078)G4 where
h = elevation in thousands of feet and
G = grade in per cent.
Use only between 5000 and 11,000 Elevation
CO 1972 Study = -30.4 + 9.6h +(2.1h-4.6)G + (-.27h +4.2)G2 +(-.04h +.54)G3
Use only between 5000 and 11,000 feet elev.
CO 1973 Study = 0.32G2 + 14.77G + 69.53 and used only at 11,000' and between +2% and -2% grade.
1964 data at 11,000'
1964 data at 6000'
1972 data at 11,000'
1972 data at 6000'
1973 data at 11,000'
107.6
75.2
69
47
94
*EPA Estimation for emissions
70 for 1964
60 for 1970
50 for 1972
40 for 1974
AVERAGE EMISSION IN grams per mile
320
280
240
200
160
120
80
40
-6%
-4%
-2%
0
+2%
+4%
+6%
GRADE

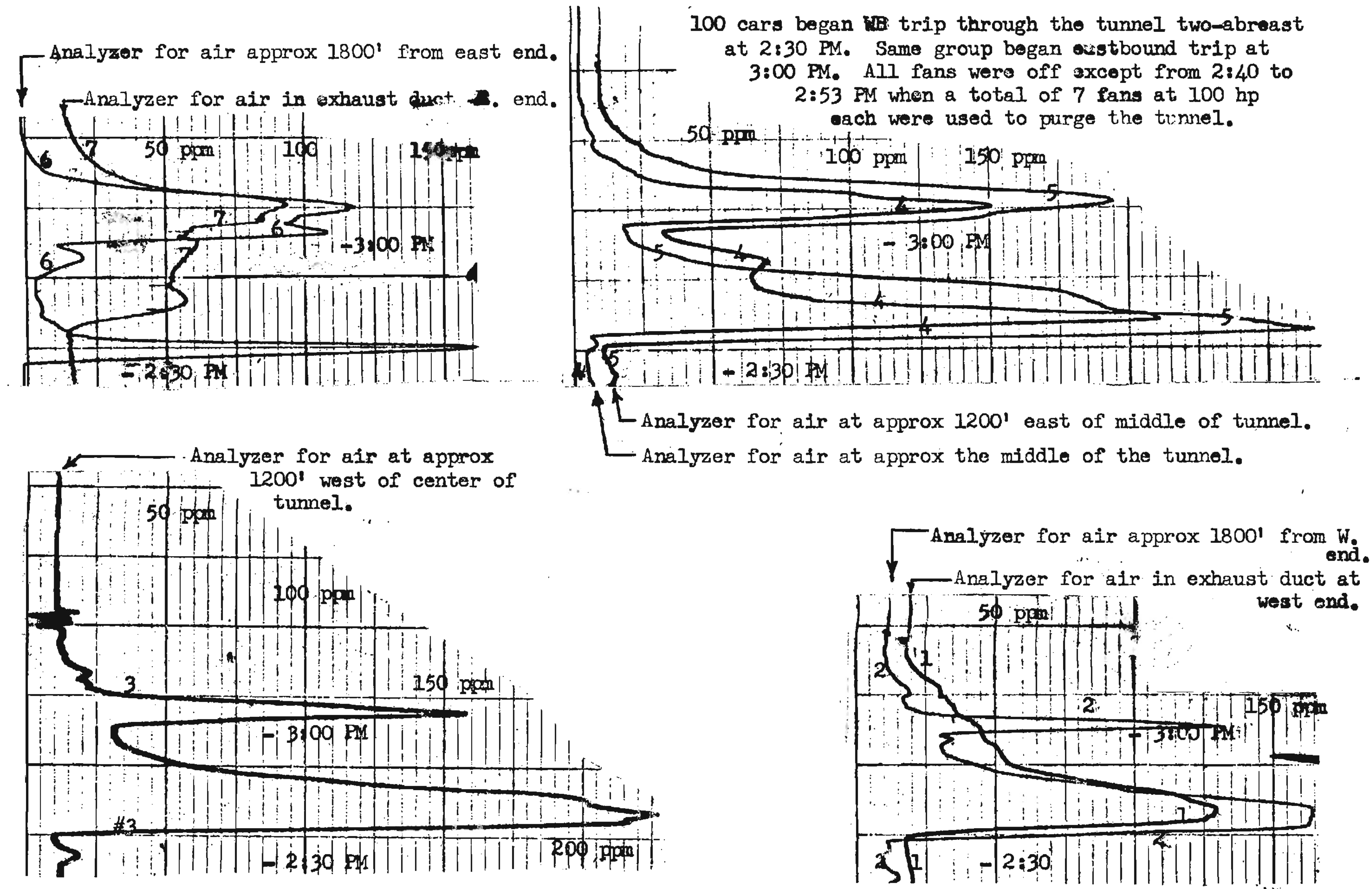


Figure 16 GRAPHS FROM CARBON MONOXIDE ANALYZERS in EISENHOWER MEMORIAL TUNNEL during TESTS FOR PISTON EFFECT.

Example of a Method to Determine Tunnel Ventilation Requirements.[10]

Assume Given: One-way Tunnel

Length = 1.5 mi.
Area = 600 $feet^2$
Elevation = 11,000 feet
Grade = +2% (eastbound),
Vehicle Speed = 60 mph
Design Traffic Volume = 1500 veh/hr (eastbound),
Wt. of Air = 25 gms/ft^3 at 20 degrees F.

Vehicle Spacing: $\frac{60 \text{ mph}}{1500 \text{ veh/hr}} \times 5280 \text{ ft/mi} = 211 \text{ ft/veh.}$

Travel Time per Vehicle in Tunnel $= \frac{1.5 \text{ mi}}{60 \text{ mph}} \times 60 \text{ min/hr} = 1.5 \text{ minutes}$

CO Output @ 11,000 ft w/2% grade = 110 gr/mi (eastbound)

Eastbound CO output = (1500 veh/hr)x(1.5 mile/veh)x(110 gr/mi)x(1 hr/60 min)

= <u>4125 gr/min</u>

Assuming no piston effect, the ventilation requirement to maintain 75 ppm is:

$$\text{Eastbound Air} = (4125)\ \frac{\text{gr}}{\text{min}} \times \frac{1 \times 10^6 \text{ parts}}{75 \text{ parts}} \times \frac{1 \text{ ft}^3}{25 \text{ gr}} = 2{,}200{,}000 \text{ cfm}$$

Assuming the piston effect exists, the ventilation requirement to maintain 75 ppm can be modified using the Gurney and Butler equation.[6] For a vehicle spacings of 211 feet, the induced air speed will be 9 mph. The displaced air resulting from the piston effect would be:

$$\text{Eastbound: } (9 \text{ mph})(600 \text{ ft}^2) \times \frac{88 \text{ ft/min}}{1 \text{ mph}} = 475{,}200 \text{ cfm}$$

Net Ventilation Requirement is:

$$2{,}200{,}000 - 475{,}200 = 1{,}724{,}800 \text{ cfm}$$

CARBON MONOXIDE CONCENTRATIONS INSIDE VEHICLES

One by-product of the 43 car emission tests through the tunnel was a determination of the pollutant concentrations in the passenger compartments of various vehicles after passing through a long tunnel. The data below shows the results of a limited study related to tunnel ventilation.

CO Concentration in ppm in Vehicle Before Trip Through Tunnel (Mostly due to instrumentation in a closed garage)	Windows Closed Except for Instrument Leads PPM Inside Vehicle	ppm After Trip Through Tunnel With Windows Open	Approximate Avg. Ambient CO Concentration in Tunnel Based On Communication From Control Room
8	30		40 ppm
5	30		40
13	40		50
125	50		60
6	37		40
12	60		65
25	60		65
30	65		65
25	52		60
3	15		30
3	15		30
15	75		60
10	60		60
27	37		50
7	48		50
40		35	50
25	21	40	50
15	30		50
15	43		50
350	250	250	Note: Car trouble
17		25	50
7	15	25	40
45	55	62	65
115		92	50
15	45		50
75	125?	Suspect Muffler leak	
20	10	15	20
150	40		45
10		35	45
10	25		45
10		2	20
3		55	55
25	25	32	45
15	30	20	45
25	37		45
25	17		20

Visibility Considerations

Reduced visibility was not a major problem in any of the tunnels investigated for this study. The 1.7 mile tunnel at the 11,000' elevation did exhibit slight light scatter after the passage of three of four diesel truck passages in the 1.64% upgrade lane.[11] However, visibility was never reduced to less than 1000' during operation of the tunnel. On occasion during brief shut down periods, the fans were run for a few seconds at full speed to clean dust out of the tunnel. Then, of course, the visibility was down to a few hundred feet due to dust.

The reason for unrestricted visibility in the Colorado tunnels was no doubt due to a low percentage of diesel trucks when there were conditions of high traffic volume. Traffic counts showed less than 1% commercial traffic when the vehicle count was over 500 vehicles per hour. It was only during low traffic hours of the night that the percentage of trucks reached 10% or 11%.

CONCLUSIONS

1. Based on this study of Colorado tunnels located in rural areas and having less than 2,400 vehicles per hour, the concentrations of pollutants in tunnels at high altitudes did not seem to be any higher than that found in tunnels at sea level. Actually, they were lower than concentrations found at street intersections in many metropolitan areas. The reason appears to be that tunnels in the high rural areas were generally scenes of very active and continuous vehicle movement, whereas, the city streets were locations of heavy stop and go traffic that excessively generated pollutants and did not diffuse them to any appreciable extent.

2. Pollutants in short tunnels located in rural areas were most likely to be concentrated in cavities or along rough, uneven walls of unlined tunnels where air flow was slow. Even then, the highest values of CO found during the tests in tunnels shorter than 1000' was 75 ppm, and this value was the result of a high CO background during a severe temperature inversion. The average CO value for 160 random readings on tunnels less than 1000' long was 8.2 ppm. The average hydrocarbon content was 4 ppm, and the average NO_x concentration was 0.17 ppm. As an example of the findings for a long tunnel, 75% of the time in the 8941' Eisenhower Memorial tunnel the mechanical ventilation needed to maintain a CO concentration lower than 50 ppm was eight fans running at 100 horsepower each.

3. The average carbon monoxide emission rate at 40 mph, which is one of the controlling factors in the design of tunnel ventilation, was approximately 1 1/2 times as much at 11,000' as at sea level. Emission rates at 'Idle' were found to be quite low (.02 pounds per minute per vehicle) for the 1973 average run of vehicles at 11,000' elevation. That 'Idle' emission value, however, was found to be reliable for only the first thirty minutes. Idling the engines for longer periods of time seemed to load up the carburetors to the point where the emission rate was almost 0.04 pounds per minute per vehicle. In case of an emergency stoppage in a tunnel, engines should be turned off as soon as possible. This additional generation of pollutants at high altitudes was apparently offset at the higher elevations by increased atmospheric turbulence, increased wind speed at higher elevations, and the fact that near the tunnels there were no urban areas that supplied a large pollutant background concentration.

4. Ambient carbon monoxide limits proposed by the Occupational Safety and Health Act of 1970 and proposed for 8 hour or even 1 hour periods by the EPA do not appear to be applicable to tunnel design. Motorists are in tunnels for very short periods of time (approximately 3 minutes in the 8941' Eisenhower Memorial tunnel, and less than 3 minutes in the shorter tunnels). The latest studies performed at Ohio State University [12]

showed that drivers had to breathe 190 ppm for 90 consecutive minutes on the average to reach 7% carboxyhemoglobin, and 400 ppm for 90 minutes to reach 14% carboxyhemoglobin. Even then, these rather severe doses of CO did not create safety hazards during test runs conducted at speeds of 30 and 50 mph. Engineers at the 11,156' level of the Eisenhower tunnel routinely breathed 200-250 ppm of CO for 30 to 60 minutes while they instrumented vehicles in a garage for emission tests through the tunnel. No ill effects were felt or observed as they drove and tested the cars through the tunnel immediately thereafter.

5. Findings for the 100 car tests at 11,000 elevation were as follows:

    a. Emission rates for about the first half-hour of idling averaged 0.02 pounds per minute. Thereafter they gradually increase to an average value which may get as high as 0.04 #/min due to carburetor load-up.

    b. The long tunnel with a transverse ventilation system was not the best place to perform experiments on piston effect because the connecting vents and ducts appear to cushion and even reverberate the air flow. The average air velocity readings for the experiments indicate an induced wind of approximately 7 mph as compared to a computed 9 mph figure from the Gurney & Butler Formula. (6)

c. Emission rates for the vehicles traveling back and forth through the tunnel at 40 mph seem to be slightly higher than those obtained by an average of individual tests on 43 representative vehicles. Never-the-less, the figures of 100 gr/mile up a 1.6% grade at 11,000' elevation, 55 gr/mile down a 1.6% grade, appear to be reasonable.

6. The concentration of carbon monoxide in vehicles traveling through tunnels appeared to depend upon the length of the tunnel and the concentration of CO in the tunnel. Vehicles traveling through the 8941 foot-long tunnel with windows closed generally had a concentration 15 to 20 ppm less than the concentration in the tunnel at the end of the trip. Vehicles traveling through the tunnel with windows open show somewhat more erratic concentrations in the passenger compartments, but these concentrations did not seem to differ much from the results found with windows closed.

7. Based on the findings from:

   a. The 1969 California Bridge Department Report[1] which stated that some means of mechanical ventilation should be provided in tunnels over 3000' long, and showed that 4700 vph will normally build-up the CO concentration to 170 ppm in a 2000' tunnel and to 250 ppm in a 3000' unventilated tunnel.

   b. The May 1972 British Tunnelling Society report by Brigadier J. Constant[13] which stated that the quantity of air required by a tunnel of given vehicular capacity increases in proportion to its length (if the natural ventilating effects at the ends are ignored).

c. The May 1971 MSA Report[16] which presented data showing that for 2000 vph, and 28 gr/mi, a mile long tunnel requires 250,000 cfm of forced air to maintain less than 150 ppm.

d. Data presented in this report that the relationship between cfm, and vph for the 8941' long tunnel is $cfm = \frac{97,000\ vph}{ppm}$ and induced air flow very nearly approximates results from the Gurney & Butler Formula[6], and assuming that:

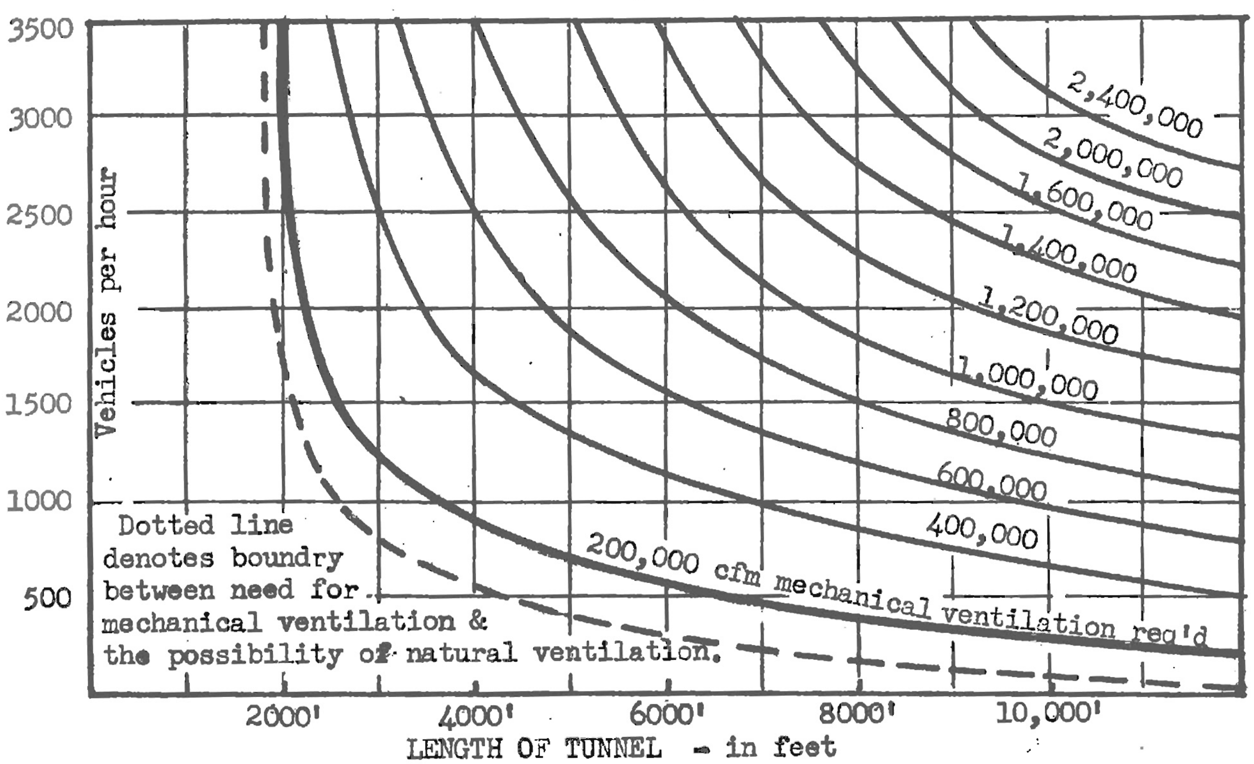
(1) The ambient air outside the tunnel has a low CO content (less than 3 ppm).

(2) The concentration as high as 150 ppm can be allowed in the tunnel.

(3) The average CO emissions are those reported in this report,

a graph can be prepared showing the required ventilation for tunnels at elevations above 5000' MSL similar to the one shown below:

Figure 17



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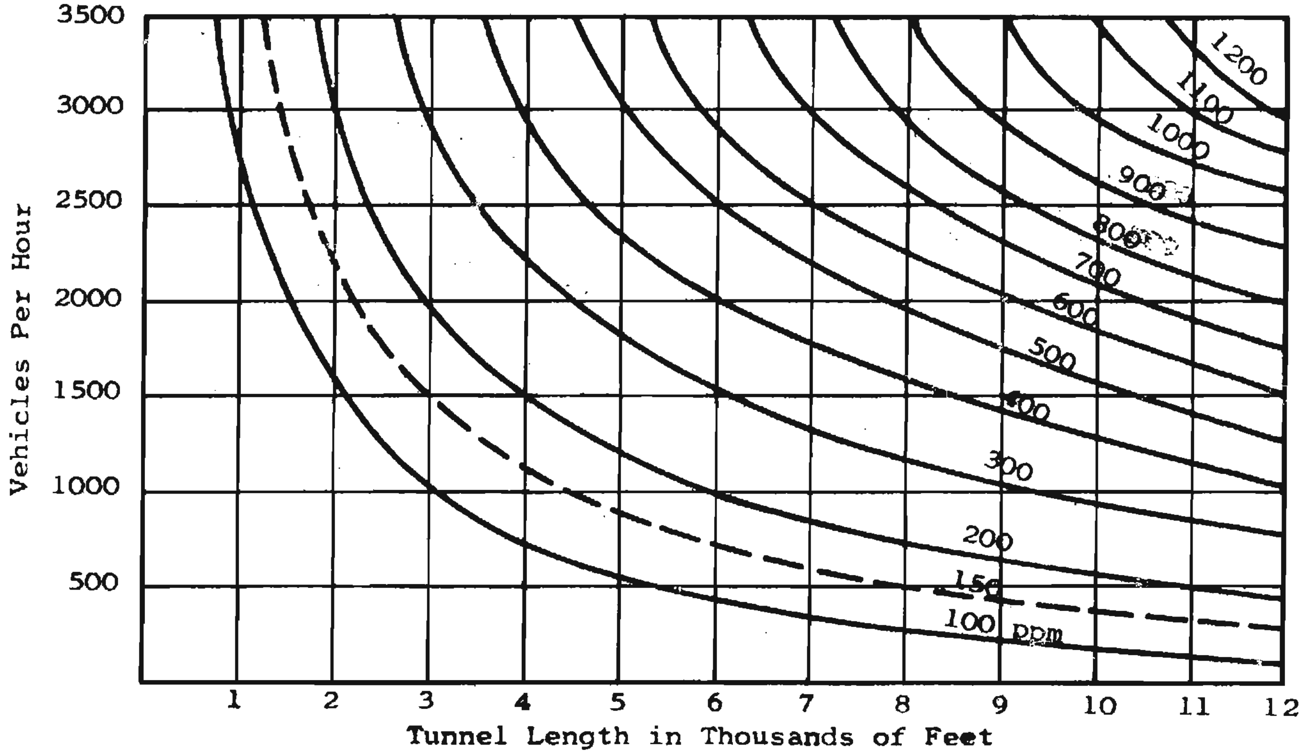
Near sea level where the vehicle emission is lower, corresponding curves are displaced upward and the dashed line may fall almost to the position of the line marked "400,000 cfm mechanical ventilation," providing that the background CO value is low.

8. Results from the use of the Gurney-Butler Induced Wind Formula, the California Line Emission Formulas, and the Mine Safety Appliance Formula were found to check closely with actual wind and concentration values in high altitude tunnels. The modified MSA formula for unvented tunnels (Box Model),

$$\text{CO Concentration} = \begin{matrix}\text{Background}\\ \text{concentration}\end{matrix} + \frac{0.0011(\text{vph})(\text{gr/mi})(\text{feet from portal})}{(\text{tunnel x-sec in ft}^2)(\text{mph wind speed})}$$

was found to be accurate and extremely useful in estimating concentrations at the center of the tunnels. Graphs like the one shown on the following page were prepared from which it appears that if the upper CO limit of 150 ppm is allowed, a tunnel may be as long as 3000 feet before mechanical ventilation is required (assuming CO-free fresh air as was always found at the high altitudes).

Figure 18



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