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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.

It was impossible to complete the work by this time because of the delay in completion of the 8941 foot long tunnel under the Continental Divide, which was intended to supply considerable data. The tunnel is now scheduled for completion in the spring of 1973 and shortly thereafter the field tests will be made. This Interim Report supplies data on short tunnels in Colorado and predicts concentrations of pollutions in longer tunnels based on formulas now in existence. Vehicle emission data for high altitudes is also reported.

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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. Heavy 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 used in design.
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 buildup of nitrogen dioxide was only to a trace in studies of diesel engine operation in a 10,000' ventilated tunnel.

3. T. Mitoni 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.

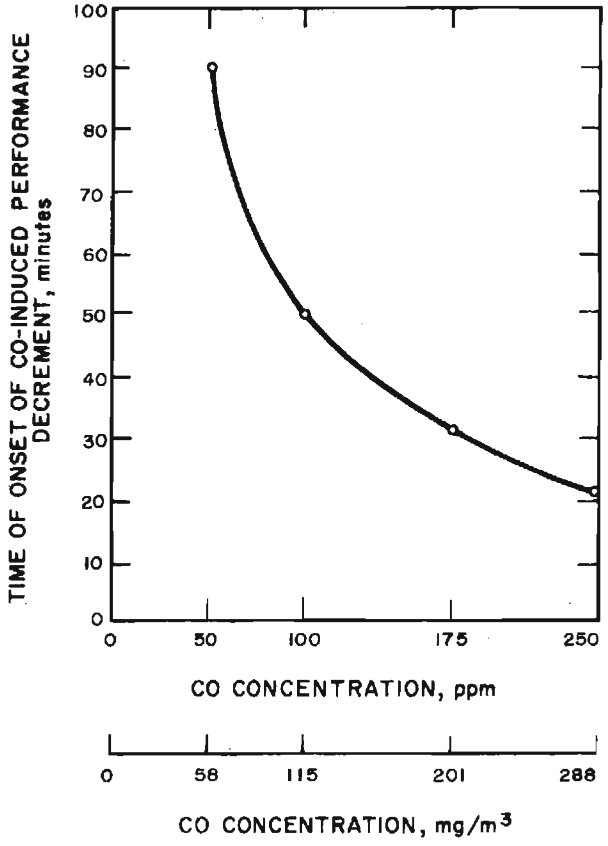
   The main variables considered likely to influence the induced flow are speed, spacing, shape and length of the vehicles; length, diameter surface roughness and entry and exit conditions of the tunnel; and pressure difference between the ends of the tunnel.

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

1. R. R. Beard(8) 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 <u>brightness discrimination</u>.

   The time of onset of CO - induced <u>auditory performance decrement</u> 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. Even a 100 ppm restriction would make tunnels less contaminated than the average city street intersection during working hours.

4. Current emergency alert levels for air pollution episodes in effect for Metropolitan Denver Air Quality Control Region 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	10.0

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:

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:

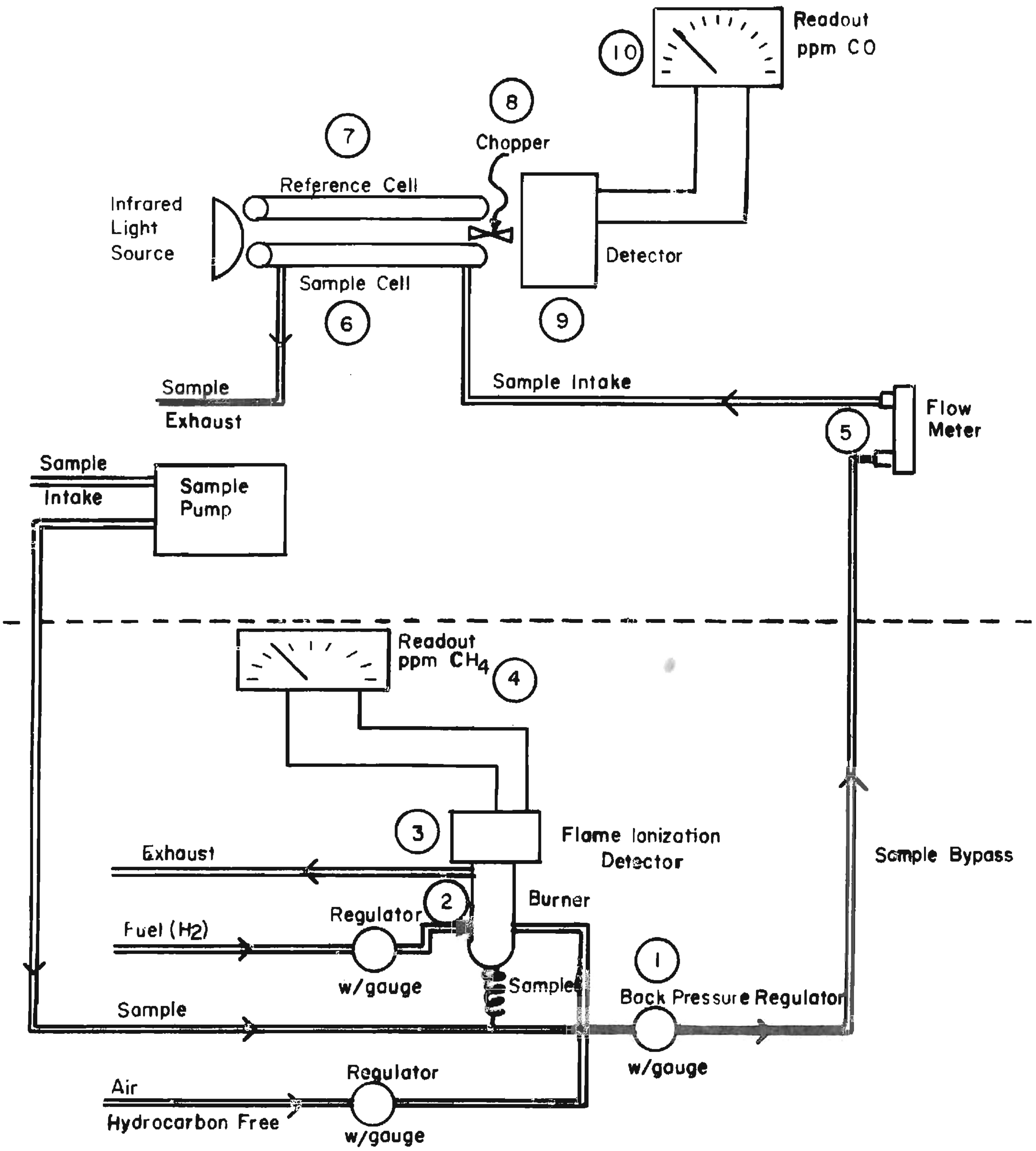
CO - Beckman IR 215A Infrared Analyzer (modified)
NO_2 - NO_x - Scientific Industries Portable Model 80
CH_4 - Beckman Model 400 Hydrocarbon Analyzer

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)

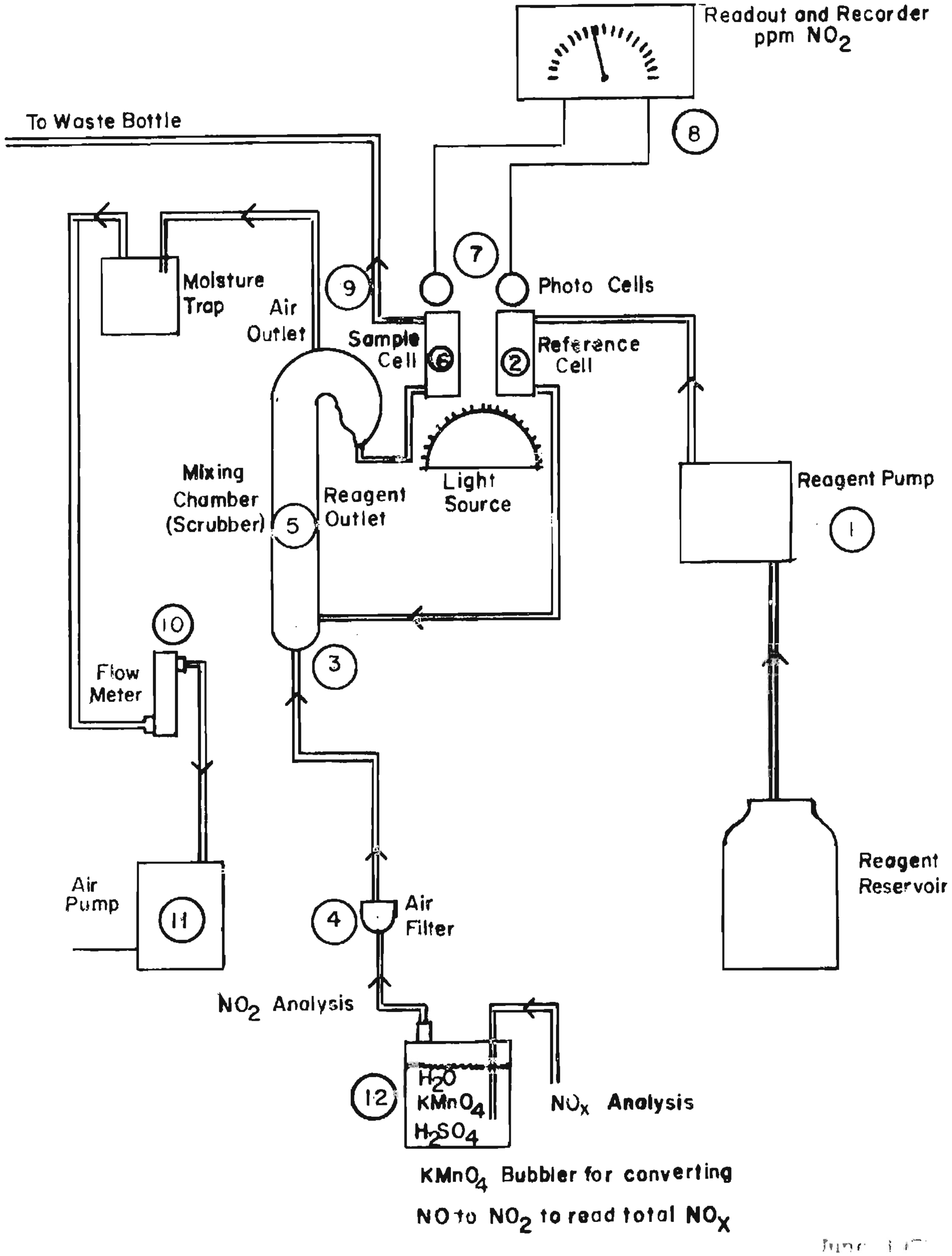


HYDROCARBON ANALYZER
(FLAME IONIZATION ANALYZER)

FIGURE 3

$NO_2 - NO_X$ ANALYZER

(VISIBLE ABSORPTION ANALYZER)



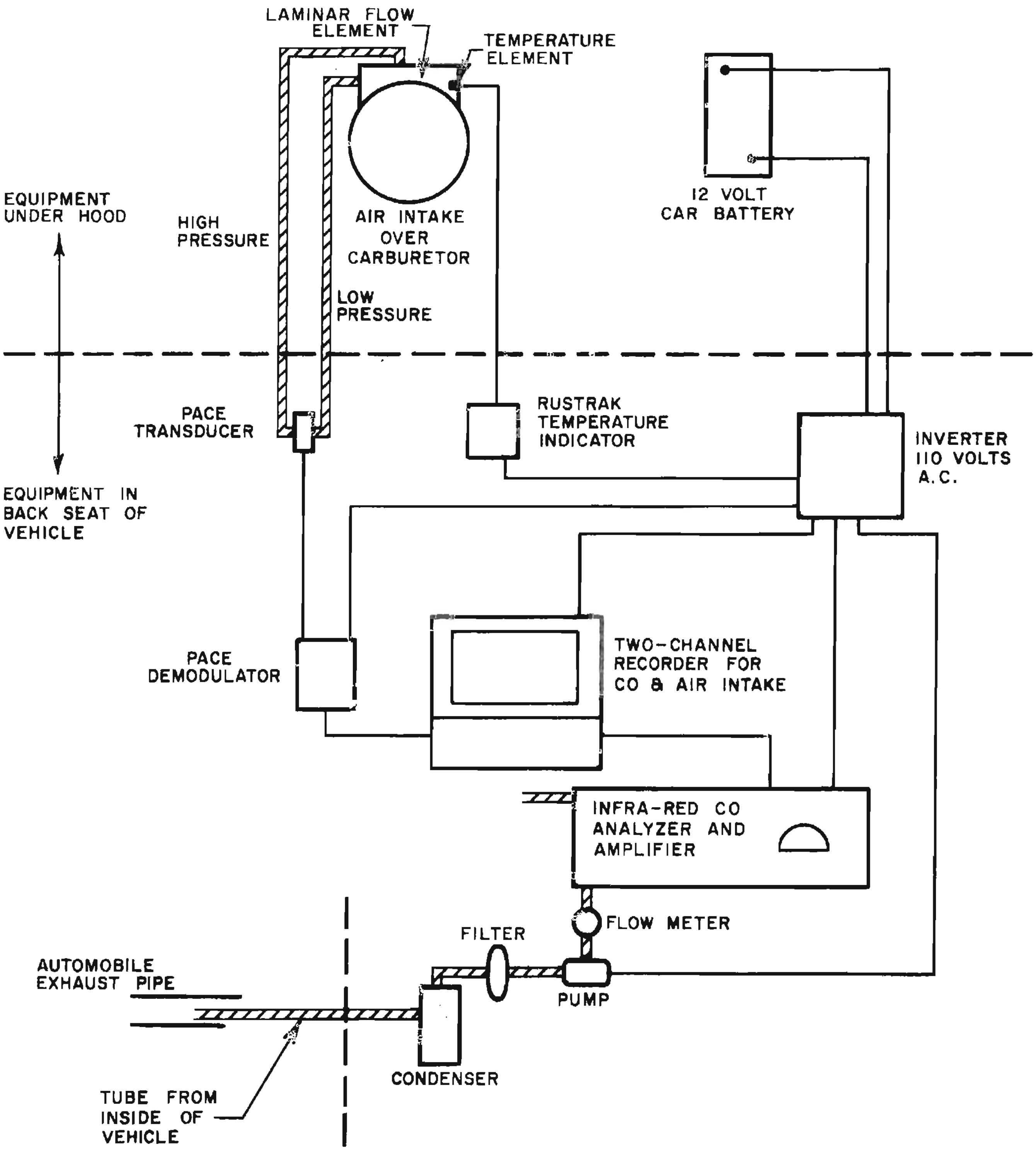
Sampling of the exhaust gas from vehicles was accomplished by a different procedure since high concentrations of CO have a tendency to revert to CO_2 and other products more readily than low concentrations. A sampling tube was inserted 2 feet into the tail pipe of the vehicles, and continuous measurements 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 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 is to come from

FIGURE 4

SKETCH OF INSTRUMENTATION USED TO OBTAIN CARBON MONOXIDE EMISSION DATA



the Straight Creek Tunnel under the continental divide when it is completed in March 1973. This data will be presented in the final report for this Project in 1973.

Results of the tests are itemized on pages 16 through 20. The NO NAME Tunnels, Idaho Springs Tunnels and Stapleton Field Tunnels are all one-way tunnels with smooth walls. 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."

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

			TUN	TUN	VEH				VEH/	WIND		TEMP		HUMID							1-2	S-R
TUNNEL ID	ALT	GR	AREA	LNTH	SPD	DATE	TIME	DIST	HR.	OUT	IN	OUT	IN	OUT	IN	CO	HC	NO-2	NO	NO-X	WAY	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
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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.

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

TUNNEL ID	ALT	GR	TUN AREA	TUN LNTH	VEH SPD	DATE	TIME	DIST	VEH/ HR.	WIND OUT	WIND IN	TEMP OUT	TEMP IN	HUMID OUT	HUMID IN	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
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CLEAR CR =3	6515	2.6	530	726	40	110971	1355	200	84	000	000	055		40		5.0		.030	.070	.100	2	R
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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
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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

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

			TUN	TUN	VEH				VEH/	WIND		TEMP		HUMID							1-2	S-R
TUNNEL ID	ALT	GR	AREA	LNTH	SPD	DATE	TIME	DIST	HR.	OUT	IN	OUT	IN	OUT	IN	CO	HC	NO-2	NO	NO-X	WAY	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

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

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

			TUN	TUN	VEH				VEH/	WIND		TEMP		HUMID							1-2	S-R
TUNNEL ID	ALT	GR	AREA	LNTH	SPD	DATE	TIME	DIST	HR.	OUT	IN	OUT	IN	OUT	IN	CO	HC	NO-2	NO	NO-X	WAY	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	306	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

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

COLORADO TUNNEL VENTILATION STUDY
TUNNEL CONTAMINATION DATA

TUNNEL ID	ALT	GP	TUN AREA	TUN LNTH	VEH SPD	DATE	TIME	DIST	VEH/ HR.	WIND		TEMP		HUMID		CO	HC	NO-2	NO	NO-X	1-2 WAY	S-R WALL
										OUT	IN	OUT	IN	OUT	IN							
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	.260	.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	.650	.720	2	R

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

ANALYSIS OF 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 tunnels was found to be very low. The average CO value for 160 readings 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 buildup inside the tunnel. The correlations might well be expected.

In both the one and two-way tunnels there was no trend established between pollutant content and traffic volume. The only explainable reason for this is that the concentrations were low and so was the traffic volume. This, together with the relatively short tunnel lengths resulted in the wind overcoming any buildup from the light traffic volumes. From a review of the literature it appears that a traffic volume of about 2,000 vehicles per hour would be necessary in a tunnel over 2,000 feet long before a strong relationship would develop between traffic and pollution concentration.

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 in almost all cases.

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 <u>40</u> ppm while the average concentration out in the middle of the tunnel was only <u>10</u> ppm.

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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 one-way tunnels, winds were generally induced inside the tunnels in proportion 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 Mitoni and Aisawa(4) 25% of the ventilation required for tunnels over 3,300' in length will be supplied by natural ventilation. Gurney and Butler(6) provide additional information. Sample calculations will be found on page 38. This example uses hypothetical data so it is not for any tunnel investigated in this study.

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

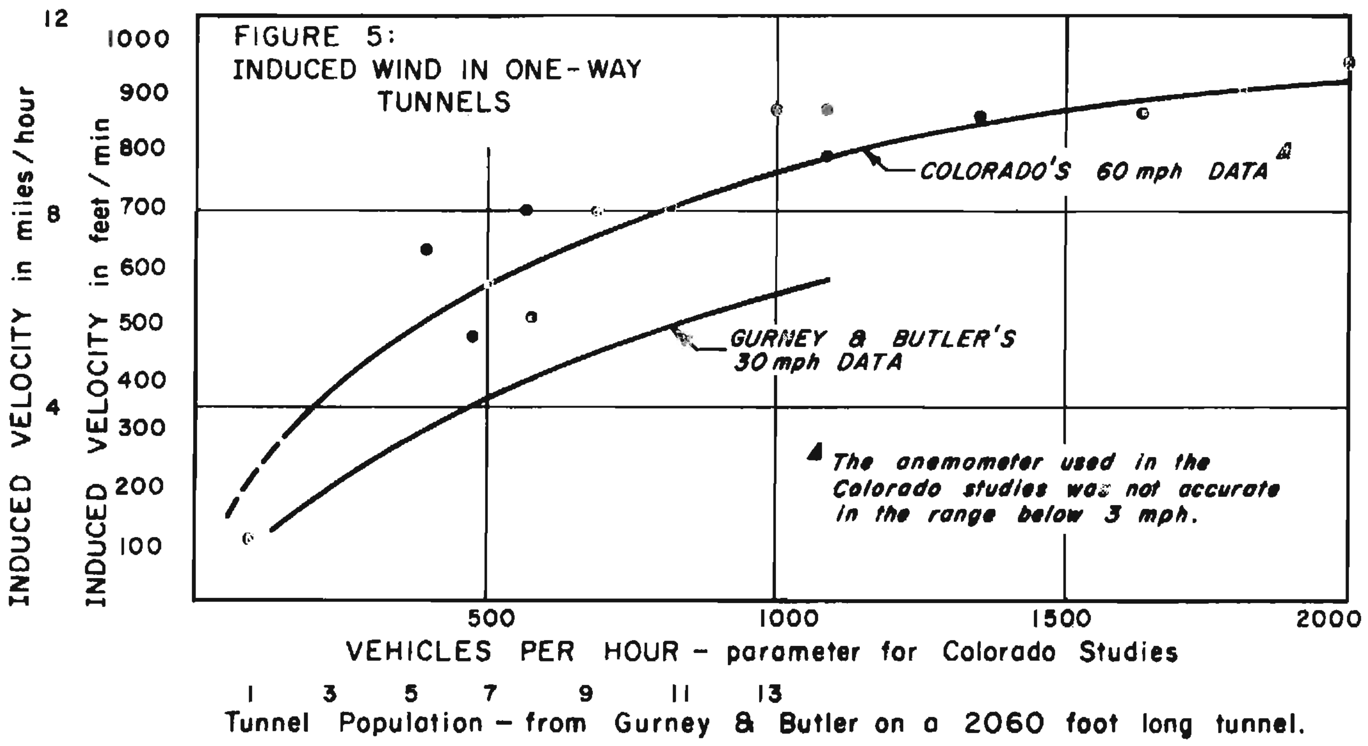


FIGURE 5:
INDUCED WIND IN ONE-WAY TUNNELS

Hydrocarbon Analysis

In this study, hydrocarbons were measured as parts per million of methane (CH_4). The peak emergency alert level considered by the Metropolitan Denver Air Quality Control Region is 20 ppm which generally corresponds to a level of 3 ppm Formaldehyde promulgated under OSHA from the Occupational Safety and Health Act of 1970.

The hydrocarbon value in tunnels measured for this study averaged 4 ppm. Eighty percent of the readings were less than 5 ppm. The higher hydrocarbon concentrations occurred during the late fall - and mostly in early November in rural areas. Readings taken during the winter months showed a large drop in HC, which probably indicates that some of the HC is from organic sources other than motor vehicles. It appears that hydrocarbon concentrations are generally quite low, although they can be near the newly established limits when the background level is high.

COMPUTED CONCENTRATION VALUES

An attempt was made to compute the concentrations in tunnels studies for this and other research projects using the California mixing cell theory, the Mining Safety Appliance Research Corporation formula and a Colorado formula 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:

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

A sketch showing the results of computations with this formula for the buildup of CO in the Stapleton Field Tunnel is shown on Figure 6.

FIGURE 6 CALCULATIONS USING THE CALIFORNIA MIXING CELL FORMULA FOR CARBON MONOXIDE CONCENTRATION IN THE UNVENTILATED TUNNEL AT STAPLETON FIELD NEAR DENVER, COLORADO (Tunnel has 8 fans-never been used)

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

where Q = source strength = $1.73 \times 10^{-7} \times$ vehicles/hr X emission in gr/mile.
K = California constant of correlation = 4.25 $1/K=K'$ from formula on p. 24.
U = wind speed in meters/second, and ϕ = angle of wind to highway ℄.

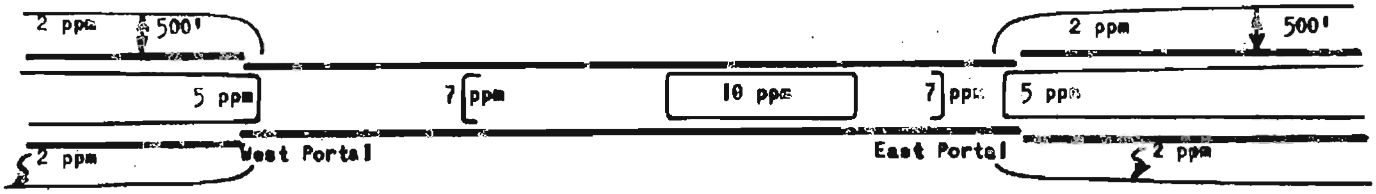
For Stapleton Field Tunnel at usual daytime conditions of WSW wind 8mph and 2000 vehicles/hr: $Q = 1.73 \times 10^{-7} \times 2000 \times 50 = 0.0173$ gr/sec/meter, and

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

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 ←



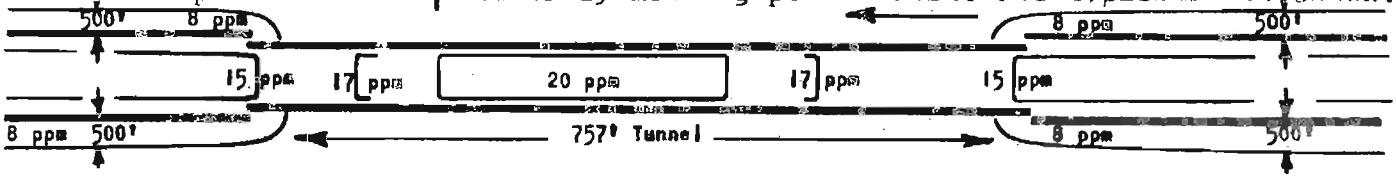
PLAN VIEW based on computations using the California formulas and typical readings of CO concentration inside the tunnel.

For usual morning condition where peak traffic is 3000 vehicles/hr and wind is 1 mph from the south: $C = \frac{1.06\ Q}{K\ U\ \text{Sin}\ o}$ where $Q = 1.73 \times 10^{-7} \times 3000 \times 50 = 0.026$.

$C = \frac{1.06\ (.026)}{4.25 \times .45 \times 1} = 0.0144\ \text{gr/m}^3$. 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:



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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 Straight Creek 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 buildup of pollutants exist inside the tunnel and uniform power ventilation is present. Figure 7 shows results of this equation applied to Straight Creek Tunnel for various conditions.

When no power ventilation exists the above equation reduces to:

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

An empirical term, $\varepsilon(X)$, 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 $\varepsilon(X)$, 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 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 16 through 20.

FIGURE 7

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

				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

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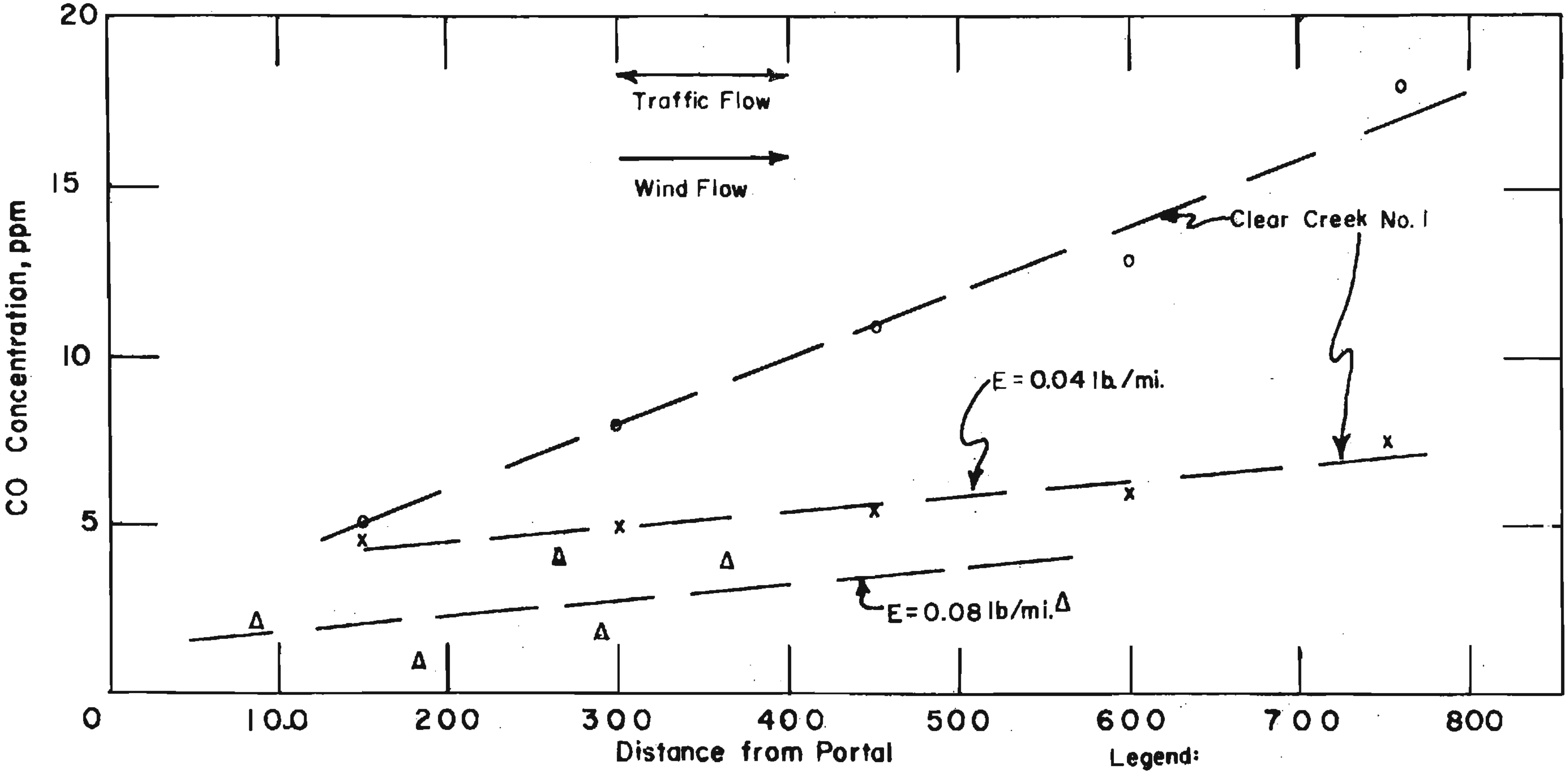
Preliminary results indicate that $\varepsilon(X)$ is zero and C is a linear function of distance. This is especially true when the natural wind dominates the traffic in two-way tunnels and the wind does not null the piston effect in one-way tunnels. This fact is illustrated in Figures 8, 9, and 10 which 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 buildup 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 buildup 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 buildup of 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 there exists an outside wind, the emission rate per vehicle (E) is indicated on the graphs. The average rate

TYPICAL
PROFILE OF CO CONCENTRATION
WITH CONSTANT CONDITIONS
IN TWO WAY TUNNELS
FIGURE 8

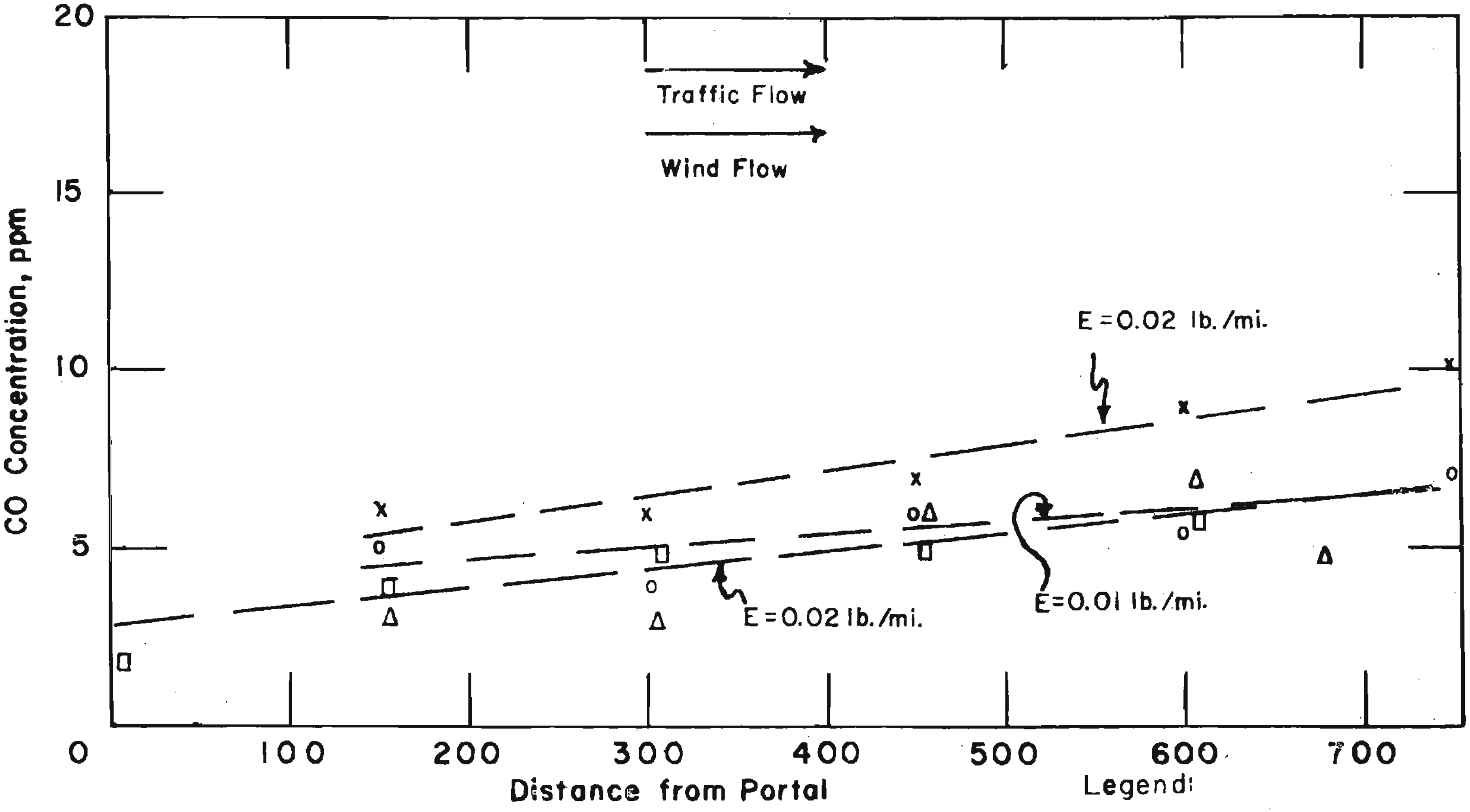


Note: Line location computed from points determined from field measurements.

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 9



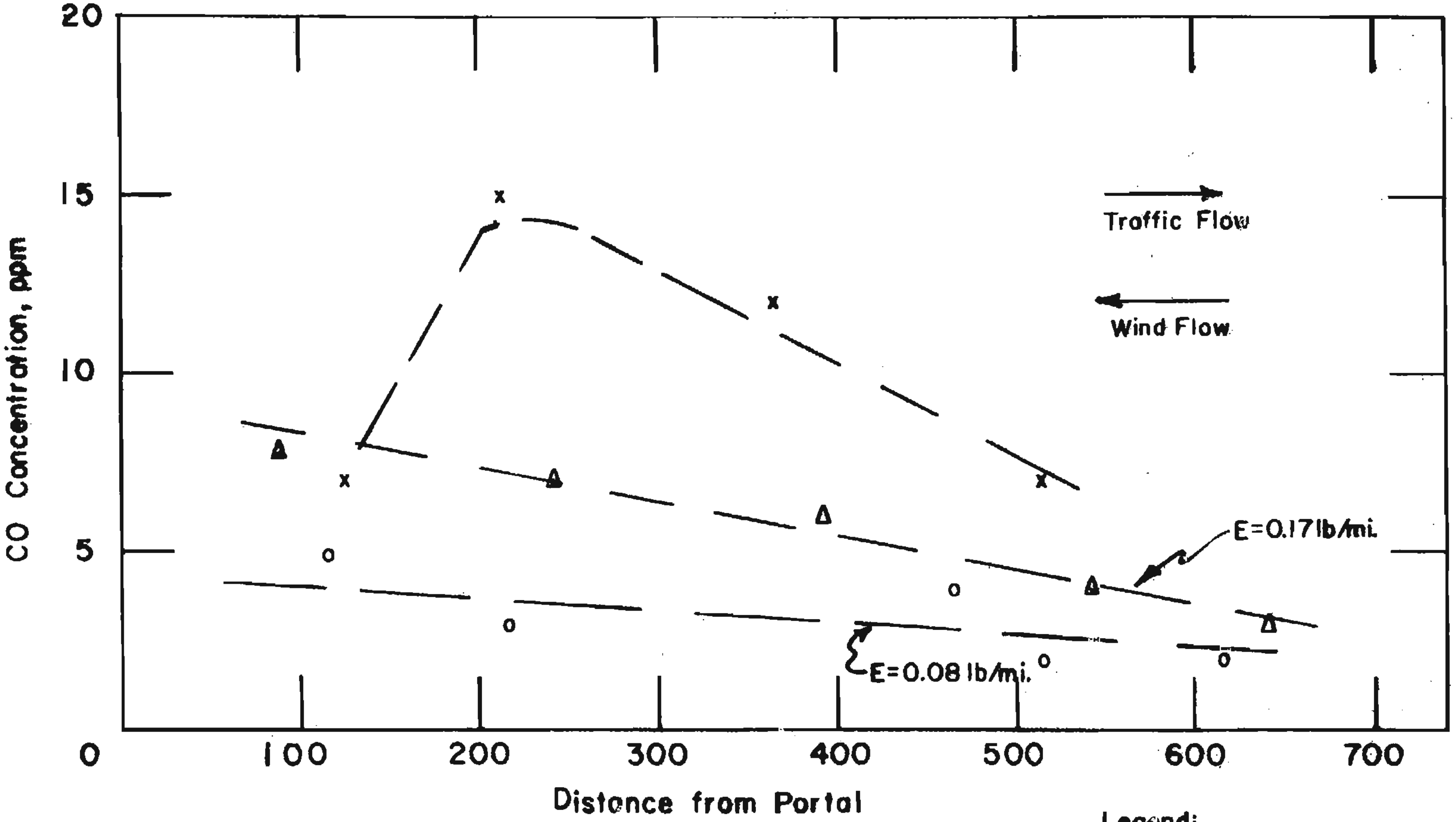
Note: Line location computed from points determined from field measurements.

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

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

FIGURE 10



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

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 buildup 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.

A non-linear buildup of pollutants exists when two-way traffic exists in a tunnel and axial air flow isn't a dominant factor. A model to predict these concentrations was hypothesized based on the conservation of mass equation. This equation reduces to the following form:

$$C = -\frac{Gy^2}{2AK} + \frac{G\ell^2}{8\ AK} + Co$$

where ℓ = tunnel length

K = Effective Dispersion Coefficient

A = Cross sectional area, y = distance from center of tunnel

C_o = Background concentration

G = Rated pollution emission = traffic vol x emission rate.

This equation assumes the maximum concentration is at the center of the tunnel or:

$$C_{max} = \frac{G\ell^2}{8\ AK}$$

AUTOMOBILE EMISSION DETERMINATIONS

Equations for the buildup 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 Authority and other agencies. The latest Environmental Protective Authority 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 Straight Creek 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 not 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

TABLE 2

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.

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

level and 11,000', and between -2% and +4% grade is:

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

where H = elevation in feet above sea level.

In 1972, five cars having displacements of 440 cubic inches, 304, 250, 95 and 70 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 is:

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

A comparison of the 1964 emission rates compared to the rates found with 1972 model cars is shown on Figure 11. The new 1972 models put out about 25% less CO at 0% grade and about 40% less at +2% grade. Actually, the new cars (in Colorado, but not in California) have been changed very little to improve pollution emission. 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 the solenoid to prevent advance timing in low gears. Naturally, 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. The IDLE control actually does affect the overall output of a car to a great extent.

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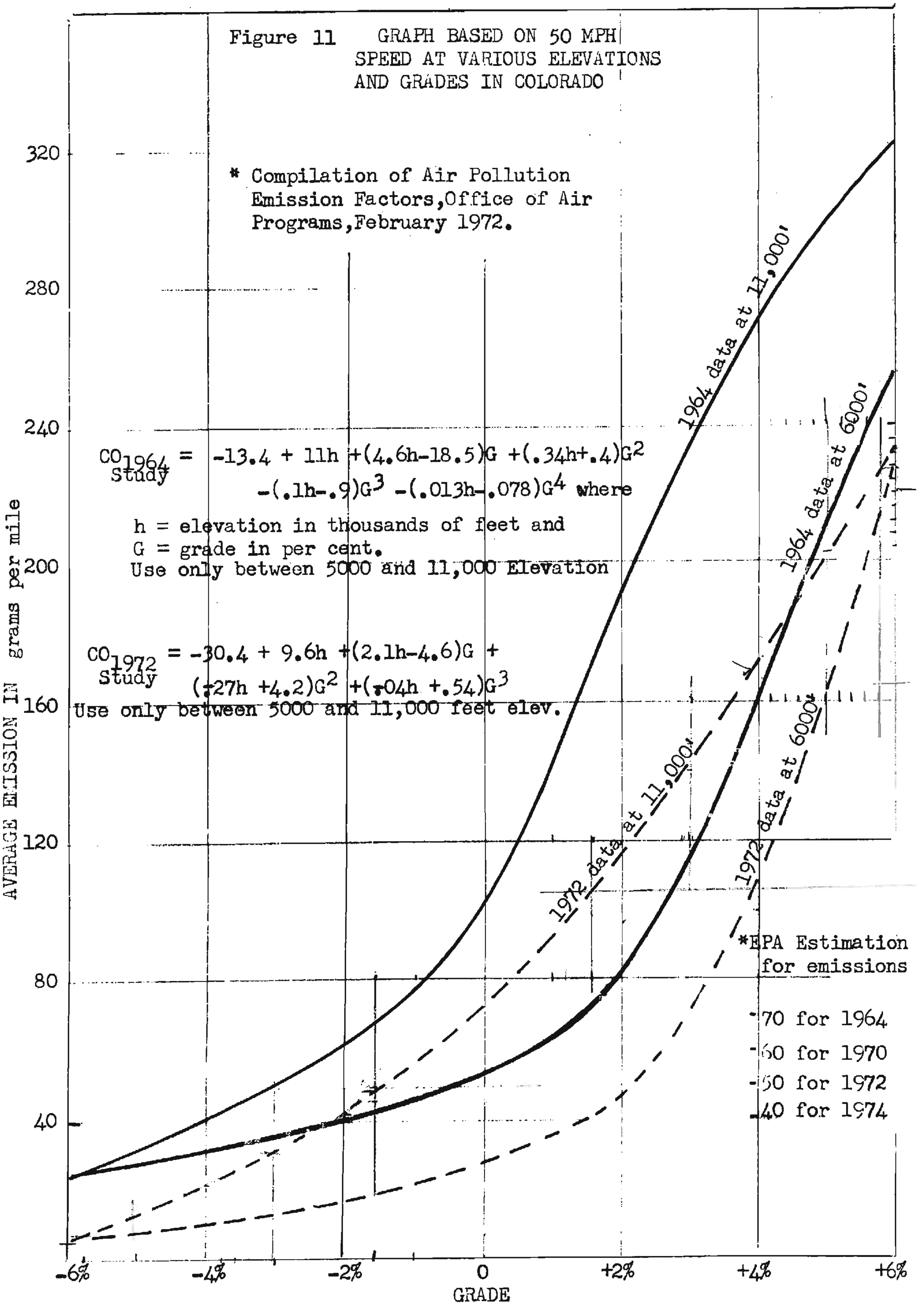
Figure 11 GRAPH BASED ON 50 MPH SPEED AT VARIOUS ELEVATIONS AND GRADES IN COLORADO



* Compilation of Air Pollution Emission Factors, Office of Air Programs, February 1972.

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

h = elevation in thousands of feet and

G = grade in per cent.

Use only between 5000 and 11,000 Elevation

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

Use only between 5000 and 11,000 feet elev.

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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), -2% (westbound)
Vehicle Speed = 60 mph
Design Traffic Volume = 1500 veh/hr (eastbound), 1000 veh/hr (westbound)
Wt. of Air = 25 gms/ft^3 at 20 degrees F.

Vehicle Spacing: $\frac{60 \text{ mph}}{1500 \text{ veh/hr}} \times 5280$ ft/mi=211 ft/veh/lane=422 ft/veh(eastbound)

317 ft/veh/lane=634 ft/veh(westbound)

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

CO Output @ 11,000 ft = 110 gr/mi (eastbound)
w/2% grade 50 gr/mi (westbound)

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

= 4125 gr/min

Westbound CO output = (1000 veh/hr)x(1.5 min/veh)x(50 gr/mi)x(1 hr/60 min)

= 1250 gr/min

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

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

$$\text{Westbound Air} = (1250\ \frac{\text{gr}}{\text{min}} \times \frac{1 \times 10^6 \text{ parts}}{75 \text{ parts}} \times \frac{1 \text{ ft}^3}{25 \text{ grms}} = 666,600 \text{ cfm}$$

Assuming the piston effect exists, the ventilation requirement to maintain 75 ppm can be modified using the Gurney and Butler equation.(6) For vehicle spacings of 472 and 634 feet, the induced air speed will be 9 and 8 mph for eastbound and westbound respectively. The displaced air resulting from the piston effect is:

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

$$\text{Westbound:} \quad (8 \text{ mph})(600 \text{ ft}^2) \times \frac{88 \text{ ft/min}}{1 \text{ mph}} = 422,400 \text{ cfm}$$

Net Ventilation Requirements are:

Eastbound: 2,200,000 - 475,200 = 1,724,800 cfm
Westbound: 666,600 - 422,400 = 244,200 cfm

CONCLUSIONS

One of the main sources of information planned for this research project was the 8,941 foot long Straight Creek Tunnel at the 11,000' altitude beneath the Continental Divide. However, unforeseen delays prevented completion of the tunnel by the time of this writing, and so this report is being submitted at the interim. The final report which will include a check-out of Figure 7 should be available within two months after the westbound Straight Creek Tunnel bore is opened to traffic in March 1973. However, completed studies of other tunnels in Colorado above 5,000' elevation make possible the following conclusions:

1. Based on the study of Colorado tunnels having less than 2,400 vehicles per hour, the concentrations of pollutants in tunnels at high altitudes do not seem to be any higher than those found at sea level. Actually, they are lower than concentrations found at street intersections in many metropolitan areas. The reason is that tunnels are generally scenes of very active and continuous vehicle movement, whereas, city streets are locations of heavy stop and go traffic that excessively generate pollutants and do not diffuse them to any appreciable extent.
2. This research on short tunnels confirms the often expressed theory that the correlation is poor between pollutant concentration and traffic density in tunnels where there are less than 2,000 vehicles per hour.
3. Pollutants are most likely to be concentrated in cavities or along the rough, uneven walls of unlined tunnels where traffic is slow and not particularly heavy. Even then, the highest values of CO found during the tests was 75, and this value

was the result of a very high background during a severe temperature inversion. The average CO value for 160 readings was 8.2 ppm. The average hydrocarbon content was 4 ppm, and the average NO_x concentration was 0.17 ppm.

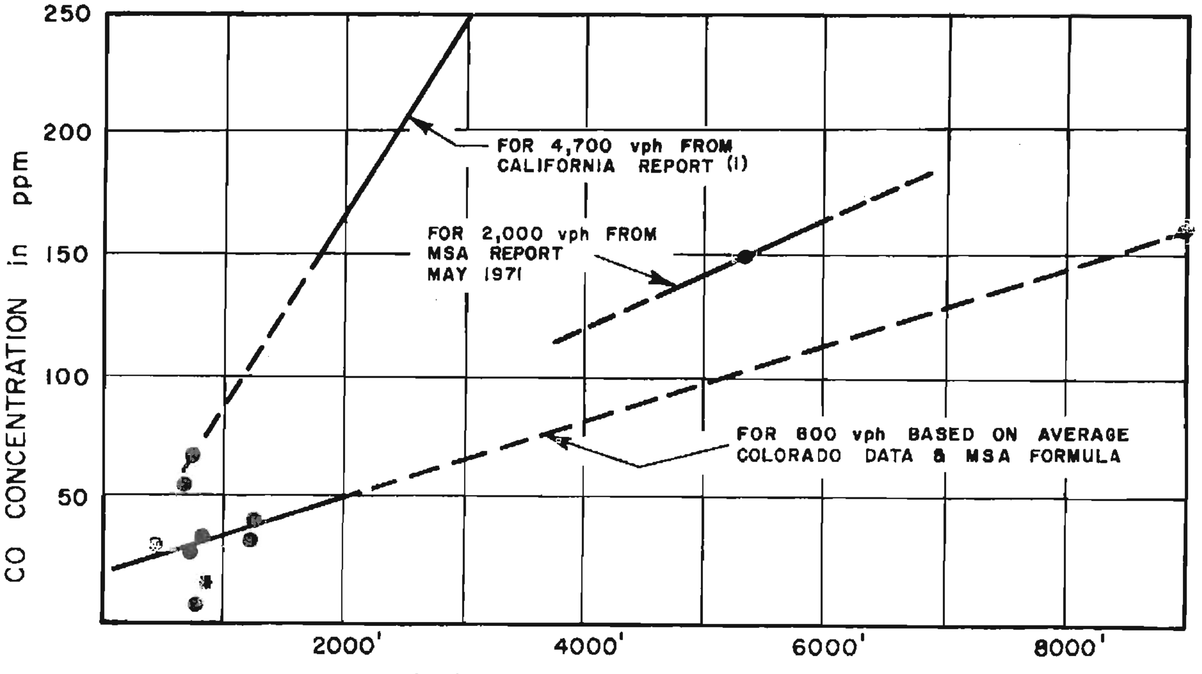
4. The carbon monoxide emission rate, which is one of the controlling factors in the design of tunnel ventilation, is approximately twice as much at 5,000' as at sea level and about twice as much at 10,000' as at 5,000 feet. This additional generation of pollutants at high altitudes is apparently offset by the turbulence and good diffusion at high altitudes. Diffusion is a function of the wind speed, and wind speed increased with altitudes as a general rule.
5. Carbon monoxide levels of less than 50 ppm proposed by the Occupational Safety and Health Act of 1970 and applied to tunnels seems extremely low. In fact, the 200 ppm level is commonly found in tunnels up to 3,000' long, and there are no reports of motorists having suffered ill effects from traveling through them. The California report recommended at 250 ppm maximum concentration value as a substitute for the 400 ppm value formerly used in tunnels. The only argument against this 200 ppm to 250 ppm level is that the effects of CO exposure and high altitude may be additive.
6. Data from the 1 2/3 mile tunnel at the 11,000' elevation will be needed to definitely answer the question as to how much

ventilation is necessary in tunnels over 1000' long at high altitudes.

It is very possible that measurements for one week in the new tunnel will provide more information than is available throughout the World at the present time about ventilation requirements at high altitudes.

7. At this time it is only possible to take pollution concentration data from the eleven Colorado Tunnels and extrapolate it on the basis of averages at a certain reasonable speed (say 50 mph), a certain expected grade (say +3%) and for a typical traffic volume on an Interstate Highway through the Colorado mountains in 1990 (say 800 vehicles per hour). For these particular values, the data was averaged and plotted below. Shown also is the line that represents data from the California Report.(1)

NO NAME TUNNEL	1,044' long	29 ppm	CLEAR CREEK NO. 2	1,069' long	39 ppm
IDAHO SPRINGS	741' "	27 "	CLEAR CREEK NO. 3	726' "	67 "
STAPLETON AIRPORT	757' "	*6 "	CLEAR CREEK NO. 5	411' "	28 "
CLEAR CREEK NO. 1	859' "	29 "	CLEAR CREEK NO. 6	588' "	55 "



*Low value due to the very inexact method of reducing data to 800 vehicles per hour.

FIGURE 12

June 1972

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