Christian Morgen,[1] M.Sc.Engin.; Jesper Schramm,[1] M.Sc.Engin., Ph.D.; Palle Kofoed,[2] B.Sc.Engin.; Jens Steensberg,[3] M.D., Ph.D.; and Peter Theilade,[4] M.D.

Automobile Exhaust as a Means of Suicide: An Experimental Study with a Proposed Model

REFERENCE: Morgen C, Schramm J, Kofoed P, Steensberg J, Theilade P. Automobile exhaust as a means of suicide: an experimental study with a proposed model. J Forensic Sci 1998;43(4): 827–836.

ABSTRACT: Experiments were conducted to investigate the concentration of carbon monoxide (CO) in a car cabin under suicide attempts with different vehicles and different start situations, and a mathematical model describing the concentration of CO in the cabin was constructed. Three cars were set up to donate the exhaust. The first vehicle didn't have any catalyst, the second one was equipped with a malfunctioning three-way catalyst, and the third car was equipped with a well-functioning three-way catalyst. The three different starting situations were cold, tepid and warm engine start, respectively. Measurements of the CO concentrations were made in both the cabin and in the exhaust pipe.

Lethal concentrations were measured in the cabin using all three vehicles as the donor car, including the vehicle with the well-functioning catalyst.

The model results in most cases gave a good prediction of the CO concentration in the cabin.

Four case studies of cars used for suicides were described. In each case measurements of CO were made in both the cabin and the exhaust under different starting conditions, and the mathematical model was tested on these cases. In most cases the model predictions were good.

KEYWORDS: forensic science, automobile exhaust, suicide, experiments, modeling

Some decades ago, before the introduction of catalytic converters, the exhaust of new automobiles frequently contained 7 to 12 vol% carbon monoxide (CO) when the engine was idling. Newer cars with emission control devices tend to emit CO levels at idle operation considerably below legal limits, i.e., exhaust containing less than 0.1% CO (1).

In Denmark, until 1971 the maximum allowable CO concentration in the exhaust of person vehicles when idling was 7 vol%. In 1984 this was reduced to 5.5% and in 1990 to 4.5%. Catalytic converters were gradually introduced during the late 1980s and became mandatory in 1990 with a maximum allowable emission of 0.5% (2).

[1] Department of Energy Engineering, Technical University of Denmark, Lyngby, Denmark.

[2] State Automobile Inspection, Regional Office, Roskilde, Denmark.

[3] County Public Health Office, Hillerød, Denmark.

[4] Institute of Forensic Medicine, University of Copenhagen, Copenhagen, Denmark.

Received 24 April 1997; and in revised form 19 Sept. 1997; accepted 22 Sept. 1997.

The aim of legislation in the U.S. from 1975 mandated the reduction in automotive emissions to improve the ambient air quality. However, an additional advantage is that a vehicle with well-functioning control and purification systems will possibly make it more difficult to successfully complete a suicide attempt using car exhaust.

The mechanism underlying the toxic effect of CO is its ability to bind to blood hemoglobin, which reduces the oxygen-carrying capacity of the blood. The affinity of CO to hemoglobin is 200 to 250 times higher than oxygen. Very high concentrations of CO in the inspired air may after a few breaths lead to loss of consciousness, convulsions and death. A concentration of 0.5 vol% (5000 ppm) quickly leads to a lethal concentration of carboxyhemoglobin (COHb) in the blood, and with 3000 ppm this may take 1 to 2 h depending on the activity of the person. Even exposure to 1000 to 1200 ppm for 1 h is dangerous to life. A simultaneous increase in the carbon dioxide (CO_2) concentration, e.g., from automobile exhaust, further increases the CO uptake through stimulation of the respiratory center of the central nervous system. Animal experiments have indicated that the ventilatory response to CO_2 is increased in CO hypoxia.

Children and aged persons with coronary sclerosis are more sensitive to CO exposure. Lethal concentrations of COHb may vary from 35% to over 75% (3–5).

Several case studies describing failed suicide attempts by emission gas poisoning in cars with catalytic converters have been published in recent years (6–9). The most frequent method used is to connect the exhaust pipe of the vehicle with the interior using, usually, a vacuum cleaner tube. The tube is inserted through one of the windows and the opening is tightened with, e.g., a blanket.

In a few published cases reconstruction experiments have been performed. In one incident a young couple was found in side an automobile, one presumably without a catalytic converter. The 26-year-old female died (41.5% COHb in heart blood) whereas the 24-year-old male was unconscious but survived. Reconstruction of the circumstances showed a sharp rise of the CO concentration with a peak value of 7000 to 8000 ppm within 25 to 35 min. The peak values were maintained for about 10 to 15 min, gradually decreasing to 3000 ppm after 90 min (10). In another case, a 48-year-old man was found dead in a recently registered car fitted with a catalytic converter, with a hose leading from the exhaust into the vehicle. The alcohol concentration in his blood was 287 mg per 100 mL with less than 5% CO saturation. In a subsequent experiment the CO_2 concentration in the exhaust emission of a car engine fitted with a catalytic converter was measured at 25%, resulting in CO_2 accumulation and concomitant decrease in oxygen in the interior compartment of the vehicle (11).

The present study was initiated to increase our knowledge of the mechanisms of suicides committed with car exhaust being led into passenger cars and to develop a model that may predict the likely mechanism in cases encountered by coroners, medical examiners, or forensic pathologists. It was part of an interdisciplinary investigation of suicides by automobile exhaust, supplementing a study of four years of experience in a Danish population (12).

The specific aims of this study have been the following:

- To investigate the transient CO concentrations in car interiors under suicidal circumstances, in order to gain a better understanding of the underlying mechanisms.
- To investigate the differences in CO concentrations inside cars with and without catalytic converters.
- To investigate the influence of starting conditions (temperature) on the CO concentration in the cabin.
- To set up a model based on physical phenomena, describing the transient CO concentrations inside the car. If the model fits the data, it is an indication that our assumptions of the physical phenomena are correct.
- To make the model simple and applicable to actual cases, thereby providing a tool for estimating the transient CO concentration in a car used to commit suicide.

Catalytic Converters

The three-way catalytic converter, which is the common type used in petrol-fueled passenger cars, is designed to reduce emissions of unburned hydrocarbons, nitrogen oxides, and carbon monoxide. A well-functioning catalytic converter reduces the emitted CO to a few hundred ppm when the engine is idling. In theory, it is therefore impossible to commit suicide by CO poisoning with a vehicle equipped with a catalytic converter, but three characteristics of the converter influence the CO emission, and are of importance for this study (13):

- The converter is operational only in a narrow fuel/air-ratio regime.
- The converter is operational only above a relatively high temperature.
- If the converter is overheated, sintering of the materials may occur. This causes the catalytic converter to require longer warm-up.

At cold start of an engine, an excessive amount of fuel is necessary to start the combustion process. This means that the catalytic converter will not be functioning in a period after start-up, until the fuel/air-ratio is stoichiometric. The fuel/air-ratio is controlled electronically, but at start-up this control is overridden to insure initiation of the combustion processes, and the choke system insures an excessive amount of fuel.

The warm-up time is an expression of the time it takes the engine and the catalytic converter to reach a certain operating temperature. It depends on the conditions under which the engine is run after start-up; high loads and engine speeds give a shorter warm-up time, while idling gives longer warm-up time.

Experimental Setup

The purpose of these experiments was to obtain an estimate of the concentration level of CO, CO_2 and O_2 in the passenger compartment (cabin) of a car used for a suicide attempt. Therefore, a standard-size car was selected to represent the potential suicide car, and different cars of newer and older technology represent the source of exhaust gas used for the suicide attempt.

The cabin used for the experiments was the cabin of a Daihatsu Charmant, sedan model. This is an average size car in Denmark with an engine displacement of 1300 cc. The cabin volume was estimated to be 2500 L. The donor vehicles used to produce exhaust gas at idle conditions are referred to as vehicle A, B, and C respectively. All three vehicles are gasoline vehicles. Further specifications for the vehicles are:

Vehicle A	Vehicle B	Vehicle C
Reg. year: 1986	Reg. year: 1995	Reg. year: 1993
eng. size: 1300 cc	eng. size: 2300 cc	eng. size: 2800 cc
mileage: 76,000 km	mileage: 3000 km	mileage: 50,000 km
non-cat.	cat.	cat.
manual choke	automatic choke	automatic choke

The exhaust gas from the donor vehicle was conducted to the cabin in a rubber tube inserted through one of the rear windows. The window was tightened with a blanket in order to use the same kind of tools that suicide victims use. The probe for collecting samples was placed at the top of the driver's seat, approximately 15 cm in front of the seat. This is where the mouth and nose of a person sitting in the seat would be.

As a first step the concentration versus time profile in the exhaust pipe of the donor car was measured in a separate test. After recording this profile the concentration versus time profile for the cabin was measured. Figure 1 shows the experimental setup. The procedure was repeated for each donor car in the following situations:

Situation 1—The donor vehicle was cold; i.e., the vehicle was left at room temperature for more than 6 h.

Situation 2—The donor vehicle was tepid; i.e., the vehicle was started and left running until the coolant temperature had stabilized. The engine was then turned off and left at room temperature for 30 min. Then the experiment was initiated.

Situation 3—The donor vehicle was warm; i.e., the engine was

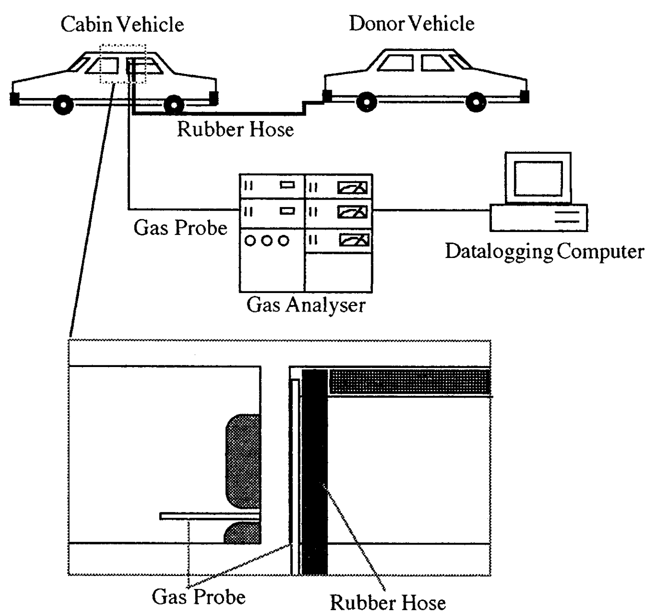

FIG. 1—*Experimental setup.*

started, and the experiment was initiated when the engine temperature had stabilized.

The components that were analyzed for in the experiments were: carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), oxygen (O_2) and unburned hydrocarbons (HC). The measurement principles of the analyzers were as follows:

CO:	NDIR (Non Dispersive Infra Red)
CO_2:	NDIR
NO_x:	Chemiluminescence
O_2:	Paramagnetic
HC:	FID (Flame Ionization Detector)

Experimental Results

CO_2 Measurements

Car A (non-cat.)—In all three cases (cold, tepid, warm) the CO_2 concentration in the exhaust increased from 0 to 15.0–15.1% very rapidly (10 s), and remained constant at this level throughout the experiments. Figure 2 (top) shows the resulting CO_2 concentration in the cabin versus time for vehicle A at tepid start. Vehicles B and C showed similar behavior. The results of model calculations are shown as well as the measurements. The model calculations will be discussed later on. Measurements at warm start showed a similar behavior. We notice from the figure that the final CO_2 level in the cabin (13%) is not the same as the stable level in the exhaust gas (15% to 15.1%). As mentioned in the Appendix, where the mathematical model is described, there is a flow of ambient air into the cabin. The final CO_2 level is therefore, in general, a little below the final level in the exhaust gas. At cold start of vehicle A both the CO_2 concentrations and the O_2 concentrations differed from tepid and warm start. The final CO_2 concentration in the cabin was approximately 7% and the final O_2 concentration was approximately 12%. This indicates a leak in the system, as explained in the Appendix.

Car B (cat.)—In all three cases (cold, tepid, warm) the CO_2 concentration in the exhaust reached 15.6% very rapidly (10 s), and remained constant at this level throughout the experiments. Measurements at cold and warm start showed similar behavior. Again the final measured level was below the stable exhaust gas CO_2 level.

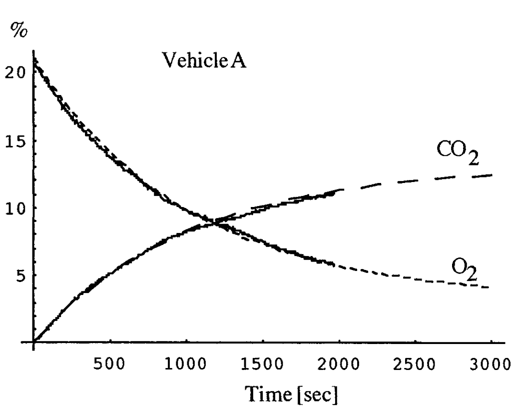

FIG. 2—*CO_2 and O_2 concentrations in the cabin after tepid start. Measured values are solid and modeled values are dashed. This figure shows the values of vehicle B, but vehicles A and C showed similar behavior.*

Car C (cat.)—In all three cases (cold, tepid, warm) the CO_2 concentration in the exhaust reached 15.6% very rapidly (10 s), and remained constant at this level throughout the experiments. Measurements at cold and warm start showed similar behavior.

O_2 Measurements

Car A (non-cat.)—In all three cases (cold, tepid, warm) the O_2 concentration in the exhaust declined from ambient air concentration at 20.7% to 0.7–0.8% very rapidly (10 s), and remained constant at this level throughout the experiments. Figure 2 shows the resulting O_2 concentration in the cabin versus time for vehicle A at tepid start. Vehicles B and C showed similar behavior. Due to the dilution of the exhaust gas the O_2 concentration does not reach 0, but remains constant at a level of 4% to 5%. The O_2 measurements at warm start showed similar behavior, while the level of O_2 in the cabin at cold start stabilized at approximately 7%.

Car B (cat.)—In all three cases (cold, tepid, warm) the O_2 concentration in the exhaust declined from 20.7% to 0.1% very rapidly (10 s), and remained constant at this level throughout the experiments. Measurements at cold and warm start showed similar behavior.

Car C (cat.)—In all three cases (cold, tepid, warm) the O_2 concentration in the exhaust declined from 20.7% to 0.7% very rapidly (10 s), and remained constant at this level throughout the experiments. Measurements at cold and warm start showed similar behavior.

CO Measurements

Car A (non-cat.)—Measurements in the exhaust gas showed that in all three cases (warm, tepid, cold) the CO concentration initially rises to a very high level, after which the concentration decreases to an almost constant, lower level. The maximum level of CO in the exhaust decreases with higher starting temperature. Unfortunately the CO concentration in the exhaust at cold start exceeded the upper level of the measurement range (9.5%), which means that we actually don't know the maximum CO concentration.

In the cold start situation the high peak in the exhaust CO causes a rapid increase in the cabin CO level. After 1 min the concentration reaches 6000 ppm. After this peak the concentration decreases slowly to approximately 3200 ppm after 30 min. In the tepid start situation, the peak in the exhaust CO causes a rapid rise in the CO concentration in the cabin, and a level of 1000 ppm is reached after 1 min. The lower CO level in the exhaust after 1 min results in a much slower rise of the CO concentration in the cabin after 1 min. The increasing slope of the curve is unexpected and it indicates a later increase in the exhaust CO concentration. In the warm start situation there is no noticeable effect of the initial peak in exhaust CO in the cabin concentration. The cabin concentration rises slowly towards the stable level of CO in the exhaust with a declining slope. This is as expected.

Car B (cat.)—In the left side of Fig. 3 the measurements of the exhaust CO content is shown versus time for case 1 (cold engine), case 2 (tepid engine) and case 3 (warm engine). In the right side of the figure the corresponding CO concentrations in the cabin are shown.

Again initial peaks are seen in all three cases (cold, tepid, warm) in the exhaust CO, and again the maximum CO value decreases

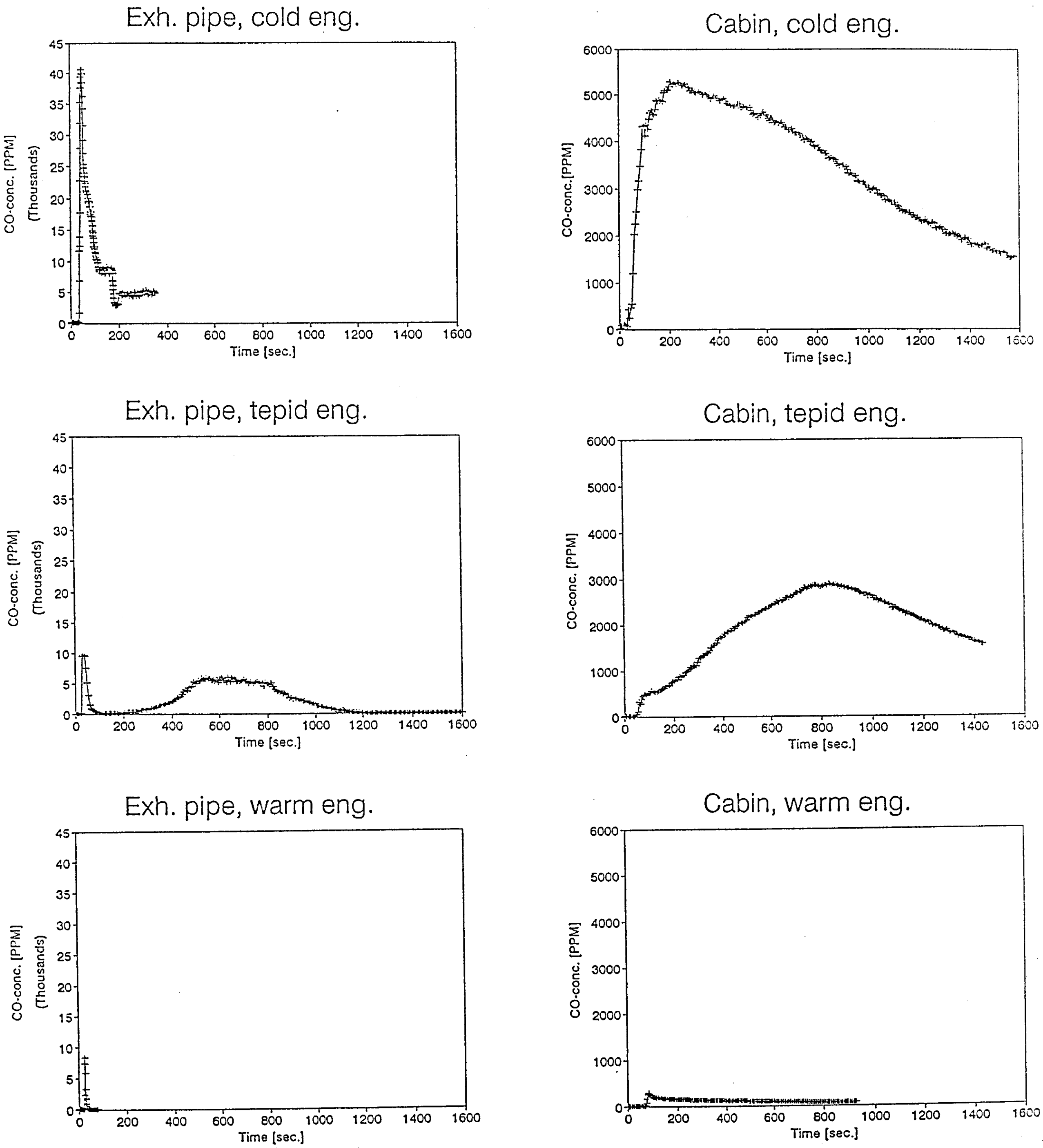

FIG. 3—*Measurements of CO concentrations in exhaust gas (*left*) and CO concentrations in cabin (*right*) for vehicle B (cat.), in the cases of cold, tepid, and warm engine respectively.*

with increasing starting temperature. In the cold start situation the stable level in exhaust CO reached after the peak is 0.5%, indicating a non-operating catalyst. In the tepid start situation, a very low level of CO in the exhaust is reached after the initial peak, but after 4 min there is an unexpected second peak in the CO concentration. The concentration increases to a level of approximately 0.5% (again indicating a non-operating catalyst), where it stays for approximately 5 min and then it falls back slowly to a very low level. In the warm start situation only a very small initial peak is observed in the exhaust CO concentration. After the peak the CO emission is very low (150 ppm).

The initial peak in the exhaust CO in the cold start situation causes a rapid rise in CO in the cabin, reaching 5500 ppm after 4 min. After the peak, the CO concentration in the cabin decreases slowly to 1700 ppm after 26 min. In the tepid start situation the initial exhaust CO peak causes a short, sharp rise in the cabin CO level, reaching 500 ppm after 1 min. This is followed by a steady, slow increase in CO level, reaching 3000 ppm after 13 min, followed by a steady, slow decline. This second peak is caused by the second peak in exhaust CO. In the warm start situation there is a very small ''hump'' in the cabin CO level caused by the initial exhaust CO peak. The CO concentration in the warm start situation never exceeds 300 ppm.

Car C (cat.)—In all three cases there are initial peaks in the exhaust CO concentrations, and again the maximum CO concentration decreases with increasing starting temperature. In all three cases the final CO concentrations in the exhaust are higher for vehicle C (0.5%) than for vehicle A (even though vehicle C has a catalytic converter and vehicle A does not). Vehicle C was a demonstration vehicle that had been used for public relations, and had been driven on the German highways, probably very often at high speeds (>150 km/h). This may have caused overheating of the catalyst, resulting in melting of the catalyst surface and consequent malfunction. In the case of vehicle C the engine was not driven warm, but was idling until the temperature of the engine coolant reached operating level (80°C). The temperature of the coolant was monitored at the built-in temperature indicator in the cabin. The experimental results show that this was not enough to heat up the catalytic converter to operating temperatures.

In the cold start situation there is a rapid increase in the CO concentration in the cabin, caused by the initial peak in exhaust CO. The CO level exceeds 7000 ppm after approximately 1 min. The recorded data are incomplete, but manual reading of the CO analyzer showed a maximum CO concentration of approximately 7600 ppm after 2 min. After this peak, the CO concentration in the cabin decreases to 4000 ppm after 20 min, where it remains constant. In the tepid start situation there is only an insignificant effect of the initial exhaust CO peak on the cabin CO concentration. The cabin CO increases slowly with a declining slope to a steady level of 4000 ppm after 30 min. In the warm start situation there is no effect of the initial exhaust peak, and the CO concentration in the cabin increases slowly with a declining slope to a steady level of 4000 ppm after 30 min.

Physiological Effects

From a toxicological point of view the following effects on persons exposed to the concentrations found in vehicles A, B, and C would be expected. This does not consider the possible added or synergistic effects of alcohol or drugs or increased sensitivity due to existing disease.

Starting vehicle A with a cold engine, after 3 min leads to a cabin concentration of 0.6% CO decreasing after 10 min to 0.3% which does not decrease further. It is likely that death would occur within 15 min. With tepid and warm engines the CO concentration increases more slowly reaching a maximum of 0.2% CO in 20 min. Taking into account the added effect of high CO_2 and low O_2 concentrations, one would expect a fatal effect within a maximum of 1 h.

Both vehicles B and C had catalytic converters. Starting with cold engines, in both cases the initial concentrations of CO are of the same order of magnitude as in the non-cat. vehicle A so that death would be expected within 15 min. With tepid engines cabin concentrations of CO are generally similar to those of vehicle A. Only when vehicle B with a well-functioning catalytic converter is started with a warm engine, a definite effect on the CO concentration occurs. The CO level is now no higher than the maximum permissible level for work environments (in Denmark 0.035%) so that no acute toxic effect is likely to result. In this case, the increasing CO_2 and decreasing O_2 concentrations should, however, likely lead to a lack of consciousness depending on the tightening of the cabin.

Modeling the Experimental Results

In order to be able to generate some reliable general data from which we can evaluate the processes that take place in the cabin as well as in the human body during a suicide attempt, we have tried to describe the concentration/time profiles mathematically in a model. The profile description has been made for CO, CO_2 and O_2. The theoretical background for the model is given in the Appendix as well as the mathematical equations that are solved in the model.

The measurements showed that the level of CO in the cabin did not reach the level of CO in the exhaust pipe when the system had stabilized. We assume that this is due to a flow of ambient air into the cabin. There may be several reasons for this flow: wind forcing air through small holes in the cabin, drag force caused by the exhaust, and dilution of the exhaust at the inlet, since the tightening of the area around the exhaust pipe cannot be perfect. All these contributions can be modeled as a single airflow. The measurements of CO_2 and O_2 are used to calculate this airflow, and the close fits of these data (Fig. 2) to the model indicate that this is a precise method.

In the following paragraphs the measured cabin concentrations are compared with the results obtained from the mathematical model.

Car A (non-cat.)—In Fig. 2 the experimental measurements of the cabin CO_2 and O_2 concentrations are compared with the results of model calculations as mentioned earlier. We notice that there is a perfect agreement between calculations and measurements, which is a solid verification of both the measurements of CO_2 and O_2 and the theory behind the model. This was also the case for start with cold and warm engine, even though the results are not shown here.

Figure 4 shows the comparison for CO. For cold and warm start there is a perfect coherence between the calculated values and the measured values. The measured CO concentrations in the cabin at tepid start and the model prediction for this case differ significantly. Apparently there has been a sudden, drastic decrease in CO

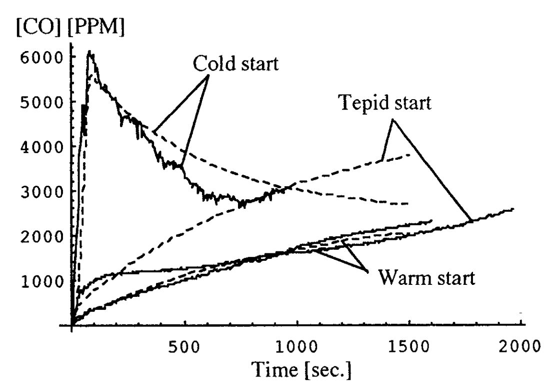

FIG. 4—*CO concentrations measured in the cabin (solid lines) compared to the model calculation (dashed lines) for Vehicle A (non-cat.).*

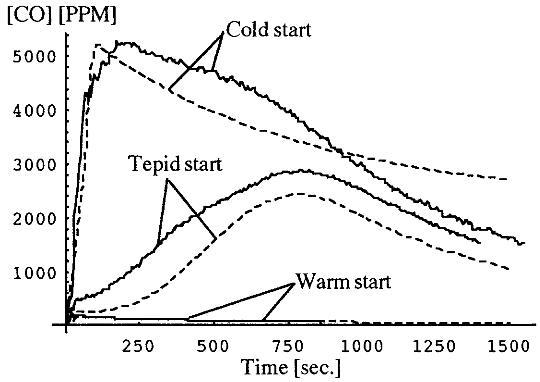

FIG. 5—*CO concentrations in the cabin (solid lines) compared to model calculations (dashed lines for cold and warm start) for vehicle B (cat.).*

emitted from the exhaust after approximately 3 to 4 min, but at the end of the experiment the CO concentration in the cabin does not seem to stabilize, indicating an ongoing increase in the CO concentration in the exhaust. Indications of such a ''second peak'' in the CO concentration in the exhaust has been seen in other vehicles (vehicle B and case studies) as well.

We have no way of checking if it truly is a ''second peak'' that causes the deviation between the model and the measurements in this case, because the exhaust level and the cabin level were measured in two different experiments. We therefore don't know exactly what the concentration/time profile is for the exhaust gas that enters the cabin. We assume that the profile did not change much from one experiment to the other. This proved to be a very precise assumption for O_2 and CO_2 but apparently there are some deviations from experiment to experiment in the CO emitted from the engines.

Car B (cat.)—As with vehicle A, models of CO_2 and O_2 show perfect agreement with experimental results.

Figure 5 shows the comparison for CO. In the cold start case there is a clear deviation between the model calculations and the measurements at the end of the experiment, showing a lower final value of CO in the cabin than predicted by the model. This might very well have been caused by deviations in CO levels in the exhaust from experiment to experiment as mentioned above.

In the tepid start situation there is a clear indication of a ''second peak,'' which is coherent with the exhaust measurement. The model calculation in this case is the sum of two model inputs, one accounting for the initial CO peak in the exhaust, and one accounting for the second CO peak in the exhaust. In the warm start situation there is some deviation in the initial phase, but the CO values in this case are so low (100 to 250 ppm) that even very small changes or inaccuracies in model parameters will cause significant changes to the calculated CO concentrations.

Car C (cat.)—As with vehicle A, models of CO_2 and O_2 show perfect agreement with experimental results.

Figure 6 shows the comparison for CO. Very accurate model predictions are obtained with vehicle C. This is due to the very stable emission of CO (0.55%) from the engine.

Case Studies

Four cases where cars have been used for suicides have been investigated. Measurements of CO concentrations in exhausts and cabins have been made after reconstructing the hose and tightening arrangements actually used. The measured CO concentrations in the cabin were compared with model predictions based on the values measured in the exhausts.

Case 1—Middle-aged male found in the cargo compartment of a small non-cat. station wagon. The motor is running and a vacuum cleaner tube leads from the tailpipe to the interior through the rear door. Tightening from the inside with blankets. CO-hemoglobin (COHb) concentration in blood: 68%; alcohol: 0; antidepressant (serotonin re-uptake inhibitor) in therapeutic concentration.

The technical reconstruction experiment showed the expected peak in CO concentration in the exhaust pipe at the beginning of the experiment for both tepid and warm start. The peak values of CO were 2.6% for tepid start and 1.6% for warm start. The duration of the peak was 30 s for tepid start and 25 s for warm start. All these values were expected, but the levels of CO in the exhaust when the emissions had stabilized showed some unexpected results: the level was higher at warm start (1.1%) than at tepid start (0.5%). No measurements were made with cold start.

The cabin measurements and the model prediction are in very good agreement in the tepid start situation with a small, sharp rise to approximately 0.1% after 2 min followed by a slow increase to 0.3% after 20 min (Fig. 7). In the warm situation there is a significant deviation between the model and the measurements. A large peak starting after 10 min and going on for approximately 15 min with maximum CO concentrations of approximately 1.2% indicates a second peak of CO in the exhaust.

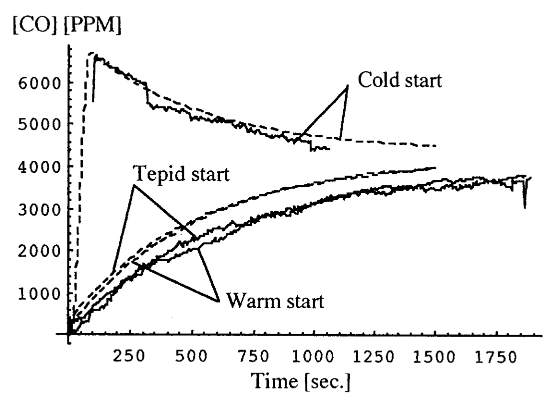

FIG. 6—*CO concentrations in the cabin (solid lines) compared with model calculations (dashed lines) for vehicle C (cat.).*

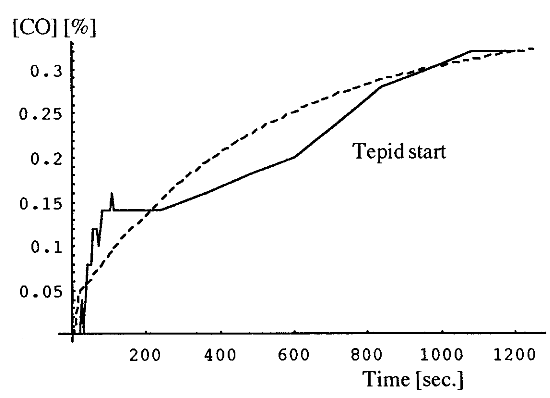

FIG. 7—*CO concentrations in the cabin (solid line) compared with model calculations (dashed line) for case 1 in the tepid start situation.*

Case 2—Middle-aged male found in driver's seat of a non-cat. person vehicle. The motor is running and a flexible plastic tube with a tight fit is mounted on the tailpipe and leads through the back hatch which is taped from the outside. COHb: 53%. Has also taken hypnotic (benzodiazepine) and analgetic (ibuprofen) tablets (no analysis).

The technical reconstruction experiments showed a peak concentration of CO in the exhaust of over 10% when starting the engine cold (with choke). After approximately 2 min the CO concentration declined to a stable level of approximately 1.6%. In the tepid situation the CO concentration in the exhaust had a short peak of 1 min duration with a maximum value of 1.7%. After declining to 0.7%, the concentration rose slowly to a stable level of approximately 2% after 10 min. When starting the vehicle with a warm engine, the CO in the exhaust had a peak of about 2 min reaching a maximum value of 2%, followed by a decline to a stable level of approximately 1.4% (toxic level).

The model predictions were consistent with the cabin measurements. Both measurements and model predictions show a steady increase in CO levels in the cabin reaching 0.8% after 25 min in the tepid situation, and 0.9% after 25 min in the warm situation. No measurements were made in the cabin for cold start, but the model predicted a sharp rise within the first 2 min to a value of 0.45% followed by a slow increase in the concentration to a value of 1% after 25 min.

Case 3—Young male found in the cargo compartment of a small non-cat. station wagon. The motor is running and a plastic sink-drain system leads from the tailpipe to the interior through the rear door. Tightening from the inside with rags. COHb: 65%. Has also been sniffing lighter gas.

The reconstruction experiment showed the expected peak at cold start with a duration of 4 min and a maximum CO level of 9%. After the peak, the CO concentration declined to under 1% for approximately 1 min followed by a rise to a stable level of 2%. When starting the engine tepid, there was a short peak (30 s) with a maximum CO level of 1.5%. After the peak there was a 1 min period with 0.2% CO, then a sharp rise to a stable level of 2%. The measurement in the exhaust pipe at warm start gave a peak of 40 s, with a maximum value of 7%, after which the concentration was stable at 2.2%.

No measurements were made in the cabin for cold start, but the model predicts a sharp rise to 0.9% followed by a slow increase, reaching 1.2% after 25 min. Due to the erratic behavior of the CO concentration in the exhaust at tepid start, no model prediction has been attempted for this situation. The measurements in the cabin at warm start gave very low values, and a check of the CO concentration in the exhaust pipe showed a concentration of approximately 0.2%, an order of magnitude less than the values measured at first. Because of this drastic change, the model prediction is very bad.

Case 4—Middle-aged male found in the cargo compartment of a small non-cat. station wagon. The motor is running and a vacuum cleaner tube leads from the tailpipe to the interior through the rear door. Tightening from the inside with tape and rags. COHb: 63%. Has also taken hypnotic (benzodiapine) (no analysis).

Measurements of the CO concentration in the exhaust after cold start showed a sharp rise to 7% followed by an erratic decline to under 1% after 8 min. The measurements after tepid start showed a similar behavior, but ending at a stable level of 1.6%. The measurements in the exhaust after a warm start showed a short (20 s) peak with a maximum CO concentration of 2.7% followed by a steady CO concentration of approximately 1.6%.

The only measurements of CO in the cabin were made after a warm start (due to technical problems). The model prediction is good for the first 6 min, but then the measurements show a slower increase in CO than the model. A window in the car had been smashed after the suicide. This window was sealed with a tarpaulin prior to the technical experiments, but it is possible that the sealing was not very efficient. The seal efficiency factor used in the model may have been too high (0.7), resulting in higher CO concentrations predicted in the car than the concentrations measured. A seal efficiency factor of 0.3 gives a good fit.

Conclusions

We have succeeded in developing a model for describing the transient carbon monoxide concentration in the passenger compartment (cabin) of a vehicle used for suicide.

Only five parameters are necessary to make a model calculation that gives a good estimate of the transient carbon monoxide concentration in the cabin during a suicide. One (M') depends on vehicle specifications only, and one (the seal efficiency factor, S) is estimated from the suicide setup. M' is the ratio of the mass flow of exhaust gases and the mass of gases in the cabin. It can be calculated from the engine displacement volume, the engine speed when idling, and the cabin volume. We have shown that the value of S, which is a measure of the tightening of the cabin, is approximately 0.7 to 0.9. The remaining three values are obtained from a simple measurement of the transient carbon monoxide concentration in the exhaust of the vehicle used for committing suicide. These three values are: the maximum CO concentration in the exhaust (CO_{emax}) shortly after start-up, the time it takes for the CO concentration in the exhaust to reach a stable value (t_{top}), and the stable concentration of CO in the exhaust (CO_{econst}).

Our measurements (both laboratory setups and case studies) have shown that there are differences from vehicle to vehicle in the transient CO emissions from the engine. Because of this, it is possible to make only a general model of the transient CO concentration in the cabin, when leading the exhaust into the cabin.

Our measurements have proven that it is possible to commit suicide by CO poisoning with a car equipped with a catalytic converter. This is the case when the engine is started cold, or if the catalytic converter is not well functioning. It is more difficult to successfully complete a suicide attempt using car exhaust when the catalytic converter is well functioning and the engine is started warm. However, if the setup is very airtight, the high CO_2 concentration and lack of oxygen in the cabin can lead to unconsciousness and possibly death.

Both measurements and models have shown peaks in the CO concentrations in the cabin at the initial stages of the suicide attempt, when starting the engine cold. Maximum values of 2 to 3 times the final constant values can occur.

APPENDIX

Description of the Mathematical Model

In order to conduct a mathematical analysis of the problem, certain simplifications are necessary:

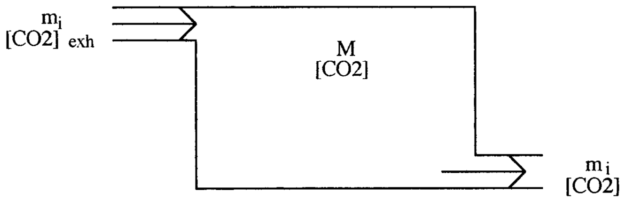

FIG. 8—*Model of car cabin with gas inlet and outlet.*

- The ''cabin'' vehicle is considered a vessel with one inlet and one outlet.
- The pressure in the cabin is considered constant.
- TThe cabin is considered to be an ideally mixed vessel.

Modeling the CO_2 Concentration in the Cabin

Since the CO_2 concentration in the ambient air is approximately zero, setting up a mass balance for the vessel shown in Fig. 8 gives the following differential equation:

$$\frac{d([CO_2]\cdot M)}{dt} = m_e\cdot[CO_2]_{exh} - m_e\cdot[CO_2] \qquad (1)$$

The measurements showed that the level of CO in the cabin did not reach the level of CO in the exhaust pipe when the system had stabilized. We assume that this is due to a flow of ambient air into the cabin. There may be several causes to this flow: wind, forcing air through small holes in the cabin, turbulence caused by the exhaust, and dilution of the exhaust at the inlet, since the tightening of the area around the exhaust pipe cannot be perfect. All these contributions can be modeled as a single airflow.

Introducing the exhaust gas mass m_e and the dilution air mass, m_d, as seen in Fig. 9, the inlet gas mass m_i is then expressed as:

$$m_i = m_e + m_d \qquad (2)$$

Combining Eqs 1 and 2, and introducing $M' = m_e/M$ and a ''seal efficiency factor'' $S = m_e/(m_e + m_d)$, gives the following equation:

$$\frac{d[CO_2]}{dt} + \frac{M'}{S}\cdot[CO_2] = M'\cdot[CO_2]_{exh} \qquad (3)$$

The analytical solution to this equation is

$$[CO_2](t) = \exp\left[-\left(\frac{M'}{S}\right)\cdot t\right] \cdot\left\{\int\left[\exp\left(\frac{M'}{S}\cdot t\right)\cdot[CO_2]_{exh}(t)\right]dt + K\right\} \qquad (4)$$

where K is an arbitrary constant.

Since the exhaust concentration of CO_2 is determined primarily by the fuel composition (assuming near-perfect combustion), most cars will have a CO_2 concentration in the exhaust gas of approximately 15%. The CO_2 concentration in the exhaust gas can be assumed constant through the relevant time span. With the boundary condition $[CO_2](0) = 0$, the solution to the differential Eq 4 is:

$$[CO_2](t) = [CO_2]_{exh}\cdot\left\{1 - \exp\left[-\left(\frac{M'}{S}\right)\cdot t\right]\right\} \qquad (5)$$

Modeling O_2

In a near-perfect combustion O_2 levels in the exhaust gas will be close to zero. Dilution of the exhaust gas at the various fittings of hoses, etc. may result in oxygen leaking into the cabin. The concentration of oxygen in the ambient air is approximately 21%. This has to be taken into account. The model of the system is shown in Fig. 10, and the differential equation is:

$$\frac{d[O_2]}{dt} = M'\cdot[O_2]_{exh} + M'\cdot\frac{(1 + S)}{S}\cdot[O_2]_{amb} - M'\cdot\frac{1}{S}\cdot[O_2] \qquad (6)$$

The solution to Eq 6 with boundary condition $[O_2](0) = [O_2]_{amb}$ is:

$$[O_2](t) = [O_2]_{amb} + S\cdot([O_2]_{exh} + [O_2]_{amb})\cdot\left\{1 - \exp\left(\frac{M'\cdot t}{S}\right)\right\} \qquad (7)$$

Determining M′

M is the mass ratio of the flow from the exhaust pipe and the residing gases in the cabin. It can be calculated by:

$$M' = \frac{Rev\cdot dvol}{60\cdot cvol\cdot 2}\cdot\frac{\rho_i}{\rho_c} \qquad (8)$$

where

Rev = engine speed, rpm
*d*vol = displacement volume, L
*c*vol = cabin volume, L

The density of the gas in the cabin, ρ_c, is proportional to the

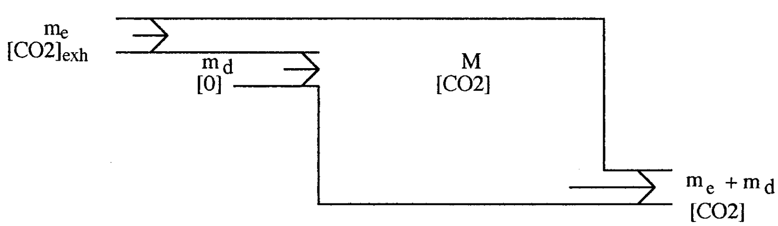

FIG. 9—*Model of car cabin with dilution of exhaust gas.*

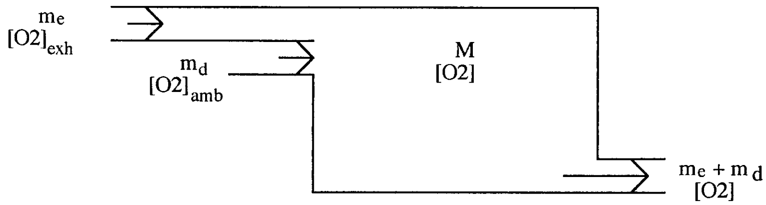

FIG. 10—*Modeling car cabin with mass flows and O_2 concentrations.*

cabin pressure, which is close to 1 atmosphere. The density, ρ_i, of the inlet gas is much lower. This is due to the pressure drop over the intake throttle, which can be quite considerable when the engine is idling. A realistic estimate of the ratio of air densities is 0.25. This value shows good accordance between models and experiments.

Determining S

S (the seal efficiency factor) is determined by comparing the CO_2 and O_2 measurements in the exhaust with the CO_2 and O_2 measurements in the cabin. By dividing the final values of CO_2 in the cabin with the values of CO_2 in the exhaust, one value of *S* is obtained. Another value of *S* is obtained by dividing the ambient O_2 concentration minus the final value of O_2 in the cabin with the ambient O_2 concentration. Equations 9 and 10 show these relations:

$$S_1 = \frac{[CO_2](\infty)}{[CO_2]_{exh}} \tag{9}$$

$$S_2 = \frac{[O_2]_{amb} - [O_2](\infty)}{[O_2]_{amb}} \tag{10}$$

Averaged values of the two obtained values of *S* for each vehicle and each test condition are then used in the CO model. The CO_2 and O_2 measurements are chosen to determine *S* because they show very little irregularity in comparison with the CO measurement. Table 1 gives calculated values of S_1, S_2, and *S* for each vehicle and each test condition.

The deviations between values of S_1 and S_2 in each case are probably due to inaccuracy in determination of the final concentrations of CO_2 and O_2 in the cabin. Most values are in the range 0.8 to 0.93, which must be considered a very narrow window for a test like this. In addition, the values obtained seem to be very realistic and give an indication of the level of tightness that is possible. However, the value for vehicle A at cold start is very low. This measurement was taken as the only measurement on the last day of experiments, and it is likely that a leak has occurred at the setup.

TABLE 1—*Values of the dilution constant* S.

Vehicle	Test Condition	S_1	S_2	S
A	cold	0.47	0.43	0.45
A	tepid	0.87	0.86	0.87
A	hot	0.87	0.86	0.87
B	cold	0.96	0.90	0.93
B	tepid	0.93	0.90	0.92
B	hot	0.93	0.90	0.92
C	cold	0.80	0.79	0.80
C	tepid	0.87	0.80	0.84
C	hot	0.87	0.80	0.84

Modeling CO

In principle, modeling the CO concentration is analoguous to modeling the CO_2 concentration in the cabin, and hence Eq 4 applies to the CO model (substituting $[CO_2]$ with [CO]).

Measurements of the CO concentration in the exhaust pipe showed a large peak immediately after start-up. The peak is due to poor combustion in the engine, and the height and duration of the peak decrease with higher starting temperature of the engine. After the peak, the CO concentrations emitted from the engine will stabilize at a constant level. If the exhaust concentration $[CO]_e(t)$ can be expressed mathematically as a function of time, it is possible to find an analytical solution to the problem. Figure 11 shows the principal pattern of the $[CO]_e$ curve.

In order to model this emission behavior, the problem is analyzed in two parts: the first part modeling the peak and the second part modeling the constant level of CO emission after the peak.

The peak is approximated by an equation of the form:

$$[CO]_{e1}(t) = \frac{[CO]_{emax}}{2} \cdot \left(1 - \cos\left[2 \cdot \pi \cdot \frac{t}{t_{top}}\right]\right)$$

where

$[CO]_{e1}(t)$ = CO concentration in exhaust gas at time t
$[CO]_{emax}$ = peak concentration of CO measured in exhaust
t_{top} = duration of peak

After t_{top}, the emission is approximated by:

$$[CO]_{e2}(t) = [CO]_{econst} \qquad ([CO]_{e2} \text{ is constant})$$

Equation 4 yields two different solutions for $[CO]_{e1}$ and $[CO]_{e2}$.

With $C = 0$ for $t = 0$, using $[CO]_{e1}$ yields (for $0 < t < t_{top}$):

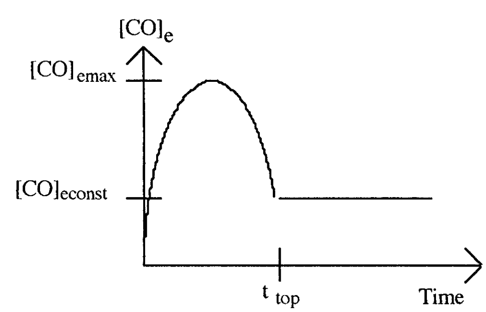

FIG. 11—*Principal behavior of CO emission from exhaust.*

$$[CO]_1(t) = \frac{[CO]_{emax} \cdot S}{([2 \cdot S \cdot \pi]^2 + [M' \cdot t_{top}]^2)} \bullet \left\{ \begin{array}{l} \cdot \left\{ 2 \cdot S^2 \cdot \pi^2 \cdot \left(1 - \exp\left[-\frac{M' \cdot t}{S}\right]\right) \right. \\ + \frac{1}{2} \cdot (M' \cdot t_{top})^2 \cdot \left(1 - \cos\left[\frac{2 \cdot \pi \cdot t}{t_{top}}\right]\right) \\ \left. - S \cdot M' \cdot \pi \cdot t_{top} \cdot \sin\left[\frac{2 \cdot \pi \cdot t}{t_{top}}\right] \right\} \end{array} \right\} \quad (12)$$

Inserting t_{top} in Eq 12 gives the value of $[CO](t_{top})$:

$$[CO]_1(t_{top}) = \frac{2 \cdot [CO]_{emax} \cdot S^3 \cdot \pi^2}{((2 \cdot S \cdot \pi)^2 + (M' \cdot t_{top})^2)} \cdot \left(1 - \text{eme}\left[\frac{M' \cdot t_{top}}{S}\right]\right) \quad (13)$$

Using $[CO]_{e2}(t)$ to solve Eq 4 and with the boundary condition $[CO]_2(t_{top} = [CO]_1(t_{top})$, the solution for $(t_{top} < t)$ is given by:

$$[CO]_2(t) = [CO]_{econst} \cdot S - \frac{\exp\left[-\frac{M'}{S}(t_{top} - t)\right] 2S^3\pi^2}{[2S\pi]^2 + [M' \cdot t_{top}]^2} \cdot \left\{ [CO]_{emax} \left(\exp\left[-\frac{M' \cdot t_{top}}{S}\right] - 1 \right) + [CO]_{econst} \cdot \left(2 + \left(\frac{M' \cdot t_{top}}{S\pi} \right)^2 \right) \right\} \quad (14)$$

Utilizing the Mathematical Model

Only three measured values are necessary to make a model prediction of the CO concentration in the cabin:

$[CO]_{emax}$ = maximum CO concentration in exhaust after start-up
t_{top} = duration of CO peak in exhaust
$[CO]_{econst}$ = constant level of CO in exhaust after peak

These three values can be obtained by simply measuring the CO concentration in the exhaust, while noting the time.

Based on engine specifics, M' can be evaluated (Eq 8). The seal efficiency factor, S, is estimated based on the setup of the specific case, e.g., how much has been done to tighten the cabin. Values in the range 0.7 to 0.9 are most probable.

By now all the variables in the two equations (12 and 14) are estimated, and all there is left is to have a computer or calculator evaluate the expressions.

Acknowledgments

The authors gratefully acknowledge Mercedes-Benz, Denmark, Falcks Redningskorps A/S (Rescue Service), and Jørgen Andersens Autoophug, Roskilde, for their contributions to this paper.

References

1. Shelef M. Unanticipated benefits of automotive emission control: reduction in fatalities by motor vehicle exhaust gas. Sci Total Envir 1994;146/147:93–101.
2. Statens Bilinspektion. Vejledning for Statens Bilinspektion. København, 1991; Oct.
3. Mueller B. Gerichtliche Medizin. 2nd ed. Berlin: Springer-Verlag, 1975;2:832–56.
4. Casarett LJ, Doull J, editors. Toxicology. The basic science of poisons. New York: Macmillan Publishing Co., Inc., 1975.
5. Gautier H, Bonora M. Ventilatory response of intact cats to carbon monoxide hypoxia. Applied Physiol.: Respir Envir & Exercise Physiol 1983;55:1064–71.
6. Landers D. Unsuccessful suicide by carbon monoxide: a secondary benefit of emission control. West J Med 1981;135:360–3.
7. Hays P, Bornstein RA. Failed suicide attempt by emission gas poisoning. Am J Psychiatry 1984;141:592–3.
8. O'Brien JT, Tarbuck AF. Suicide and vehicle exhaust emissions. BMJ 1991;304:1376–7.
9. Wagg AS, Aylwin SJB. Catalytic converter and suicide risk. Lancet 1993;342:1295.
10. Tsunenari S, Kanda M, Yonemitsu K, Yoshida S. Suicidal carbon monoxide inhalation of exhaust fumes. Investigation of cases. Am J Forensic Med Pathol 1985;6:233–9.
11. Atkinson P, Langlois NIE, Adam BJ, Grieve JHK. Suicide, carbon dioxide, and suffocation. Lancet 1994;344:192–3.
12. Theilade P, Steensberg J, Kofoed P, Schramm J, Morgen C. Automobile exhaust as a suicidal means. Four years of experience in a Danish population. Archives of suicide research.
13. Heywood, JB. Internal combustion engine fundamentals. Singapore: McGraw-Hill, 1988.

Additional information and reprint requests:
Jesper Schramm
Dept. of Energy Engineering
Bld. 403, DTU
DK-2800 Lyngby, Denmark