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Determining the frequency of open windows in motor vehicles: A pilot study using a video camera in Houston, Texas during high temperature conditions

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Researchers have developed a variety of computer-based models to estimate population exposure to air pollution. These models typically estimate exposures by simulating the movement of specific population groups through defined microenvironments. Exposures in the motor vehicle microenvironment are significantly affected by air exchange rate, which in turn is affected by vehicle speed, window position, vent status, and air conditioning use. A pilot study was conducted in Houston, Texas, during September 2000 for a specific set of weather, vehicle speed, and road type conditions to determine whether useful information on the position of windows, sunroofs, and convertible tops could be obtained through the use of video cameras. Monitoring was conducted at three sites (two arterial roads and one interstate highway) on the perimeter of Harris County located in or near areas not subject to mandated Inspection and Maintenance programs. Each site permitted an elevated view of vehicles as they proceeded through a turn, thereby exposing all windows to the stationary video camera. Five videotaping sessions were conducted over a two-day period in which the Heat Index (HI) – a function of temperature and humidity – varied from 80 to 101 degrees F and vehicle speed varied from 30 to 74 mph. The resulting videotapes were processed to create a master database listing vehicle-specific data for site location, date, time, vehicle type (e.g., minivan), color, window configuration (e.g., four windows and sunroof), number of windows in each of three position categories (fully open, partially open, and closed), HI, and speed. Of the 758 vehicles included in the database, 140 (18.5 percent) were labeled as "open," indicating a window, sunroof, or convertible top was fully or partially open. The results of a series of stepwise linear regression analyses indicated that the probability of a vehicle in the master database being "open" was weakly affected by time of day, vehicle type, vehicle color, vehicle speed, and HI. In particular, open windows occurred more frequently when vehicle speed was less than 50 mph during periods when HI exceeded 99.9 degrees F and the vehicle was a minivan or passenger van. Overall, the pilot study demonstrated that data on factors affecting vehicle window position could be acquired through a relatively simple experimental protocol using a single video camera. Limitations of the study requiring further research include the inability to determine the status of the vehicle air conditioning system; lack of a wide range of weather, vehicle speed, and road type conditions; and the need to exclude some vehicles from statistical analyses due to ambiguous window positions.
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Introduction

The US Environmental Protection Agency (EPA) employs a variety of computer-based models to estimate population exposure to air pollution (Johnson, 1995; Ott et al., 1988; US EPA, 1991). These models typically estimate exposures by simulating the movement of specific population groups through defined microenvironments. The accuracy of the resulting exposure estimates is highly dependent on the validity of the probabilistic algorithms used to estimate pollutant concentrations in each microenvironment. In the more sophisticated models, a mass balance model is used to calculate the pollutant concentration within an enclosed microenvironment as a function of outside concentration, air exchange rate, decay rate, and deposition rate, as appropriate. In motor vehicles, air exchange rate is significantly affected by vehicle speed, window position, vent status, and the use of air conditioners and heaters. Two of these factors, vehicle speed and window position, can be monitored by external observers. A pilot study was conducted in Houston, Texas, during September 2000 to determine whether useful information on window position as a function of speed and other factors could be obtained through the use of video cameras. This article describes the procedures used in this study, presents results of a statistical analysis of the data, and presents recommendations for follow-up studies.

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Methods

Selection of Study Area and Monitoring Sites

The primary purpose of the pilot study was to test an approach for gathering data on window position that could be employed in later, more comprehensive studies. Researchers also hoped to obtain data that would be immediately useful to exposure modelers requiring window position data representative of high temperature/humidity conditions in metropolitan areas with heavy vehicle use. In addition, researchers desired a location where older vehicles with non-functioning air conditioning systems would be well-represented within the vehicle mix. The Houston metropolitan area was selected as the general area for the pilot study because (1) the city tends to be hot and humid during the summer, (2) the population of Houston contains a substantial population of residents in the lower socioeconomic stratum, and (3) the metropolitan area includes outlying communities not subject to vehicle emission inspection and maintenance (I&M) programs. Researchers expected these outlying communities to have relatively large populations of older, poorly-maintained vehicles without functioning air conditioners. The pilot study was conducted in mid-September 2000 during a period when the Heat Index (HI)–a function of temperature and relative humidity–varied between 80 and 101 degrees F.

The Houston I&M district includes all of surrounding Harris County, but not adjacent counties. Researchers selected three videotaping locations near the Harris County border (Figure 1) with the goal of including vehicles from outside the I&M district. These sites included one location along an interstate highway and two locations along arterial roads. Diagrams of the sites are provided in Figures 2–4. Each site permitted an elevated view of vehicles as they

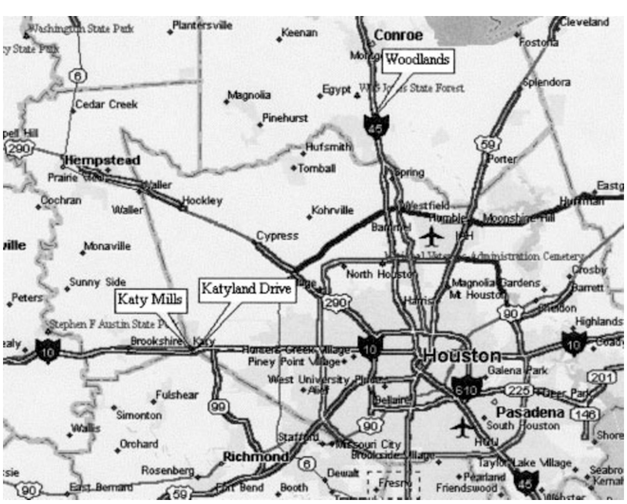

Figure 1. Map of Houston study area showing videotaping locations.

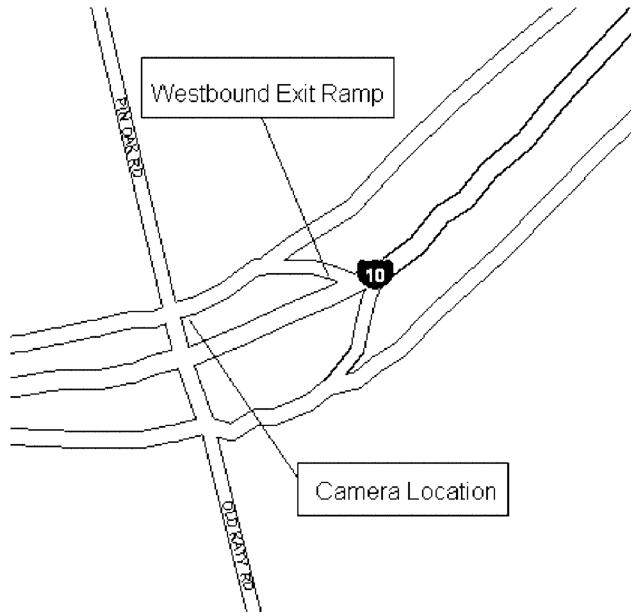

Figure 2. Sketch of Katy Mills videotaping site.

proceeded through a turn, thereby exposing all windows to the stationary video camera.

The interstate highway site, hereafter referred to as "Katy Mills", was located along the westbound exit ramp of Interstate 10 at Pin Oak Road, near the town of Katy, TX. This section of I-10 has three westbound lanes and three eastbound lanes. The exit ramp filmed in this study has two lanes. This exit experiences high traffic volume because it serves the Katy Mills outlet mall. The video camera was situated at the end of the exit ramp, near the Pin Oak Road overpass.

One arterial road site, referred to as "Katyland Drive", was located at the intersection of Katyland Drive and US Route 90 in the town of Katy, TX. The camera was set up at a safe location on a railroad grade, one of the few elevated spots in Katy. Vehicles traveling south on Katyland Drive were videotaped as they turned left onto US 90. Katyland Drive has one lane in each direction for through traffic and one left turn lane in the southbound direction.

The other arterial road site, called "Woodlands", was located at the intersection of Grogan's Mill Road and Research Forest Drive in the community of The Woodlands. The Woodlands is situated in Montgomery County, north of Houston along Interstate 45. Traffic was videotaped turning left from Grogan's Mill Rd. onto Research Forest Dr. Grogan's Mill Road is a one-way street with one left turn lane and one combination left/right turn lane. The video camera was again set up on a slightly elevated site near the intersection.

The two arterial road sites were located along distinctly different types of roads. Katyland Drive runs along the

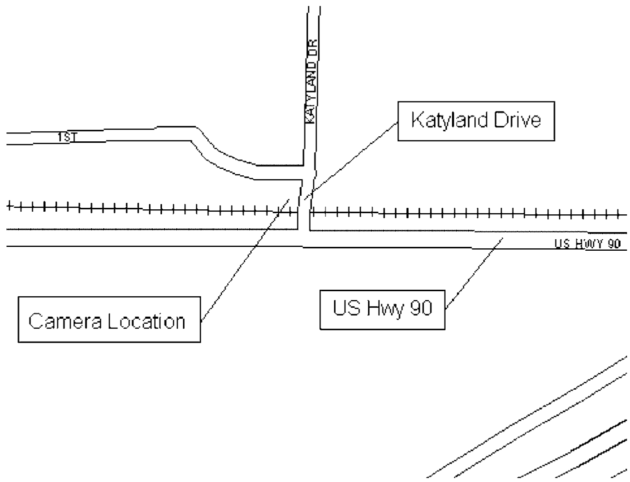

Figure 3. Sketch of Katyland Drive videotaping site.

edge of town, away from the downtown area of Katy. Land use in the vicinity of the videotaping site includes light and medium industry, while a school and athletic fields are located along Katyland Drive in the opposite direction of traffic flow, upstream of the camera. Vehicles filmed by the video camera were heading out of town toward an Interstate 10 interchange approximately 1 mile away. In contrast, Grogan's Mill Road in The Woodlands is a suburban parkway carrying local traffic. Field staff did not observe schools, industry, or retail locations in the area. Vehicles on the videotape were heading away from Interstate 45.

The Katy Mills location can be characterized as a rural interstate site. The nearby Katy Mills outlet mall appeared to have been recently constructed and was located away from other development. Field staff noted that most of the vehicles filmed for this study were traveling toward the outlet mall.

At the Katy Mills interstate site, the video camera was situated at an elevated location near a freeway exit ramp so that each window in exiting vehicles became visible as the vehicle traveled along the ramp. At the arterial road sites (Katyland Drive and Woodlands), the camera was stationed on an elevated position overlooking an intersection with turning vehicles. As each vehicle turned through the intersection, all windows of the vehicle became progressively visible to the video camera. At all three locations, vehicles in the camera's field of view were likely moving at speeds slower than the main traffic flow. However, researchers assumed that the window positions observed under these conditions were representative of vehicles moving at the flow speed of the main roadway. Consequently, the speed assigned to each vehicle in the study database is the traffic flow speed of vehicles moving on the main roadway prior to turning.

Field staff conducted three videotaping sessions at the Katy Mills (interstate) location, and one session each at the Katyland Drive and Woodlands sites. Table 1 lists the date and nominal time period of each taping session as well as the observed ranges of vehicle speed and HI. Vehicle speeds varied from 30 to 74 mph during the five taping sessions. HI was calculated by the formula

$$\begin{aligned} HI = & -42.4 + (2.049)(T) + (10.14)(RH) - (0.2248)(T) \\ & \times (RH) - (6.838\times10^{-3})(T)^2 - (5.482\times10^{-2})(RH)^2 \\ & + (1.229\times10^{-3})(T)^2(RH) + (8.528\times10^{-4})(T) \\ & \times (RH)^2 - (1.99\times10^{-6})(T)^2(RH)^2 \qquad (1) \end{aligned}$$

in which HI is expressed in degrees F, RH is the relative humidity expressed in percent, and T is the temperature in degrees F. This formula was developed by the US National Weather Service (NWS) (Rothfusz, 1990) to approximate its widely used HI table. The NWS HI table is derived from a complex biometeorological model developed by Steadman (1979), which uses physiological, clothing, and meteorological variables to calculate skin heat transfer rates and thereby "apparent" temperature at various temperature and humidity conditions. During the taping sessions, temperature varied from 81 to 95 degrees F, relative humidity varied from 28 to 55 percent, and HI varied from 80 to 101 degrees F. No precipitation occurred during any of the taping sessions, and roadways were dry in all cases.

Researchers observed markedly different weather conditions on the two days of videotaping. The first day

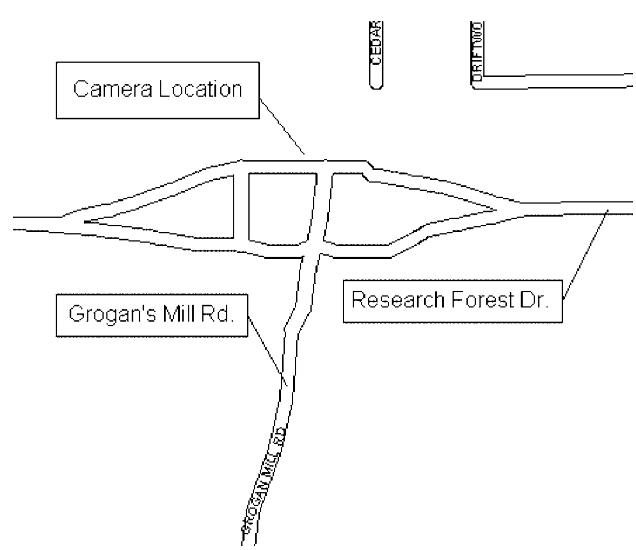

Figure 4. Sketch of Woodlands videotaping site.

Table 1. Characteristics of videotaping sessions.

Location	Date	Time period (h)	Range of vehicle speeds [miles/h]	Range of HI [°F]	Number of vehicles initially included in master database	Number of vehicles with valid data for statistical analysis
Katy Mills	Friday, 9/15/2000	1150–1213	59–70	100	178	152
	Friday, 9/15/2000	1829–1853	63–70	97–100	174	152
	Saturday, 9/16/2000	1104–1123	64–74	80–81	176	149
Katyland Drive	Friday, 9/15/2000	1614–1707	30–48	97–101	169	153
Woodlands	Saturday, 9/16/2000	1333–1359	37–48	85–88	171	152
Total					868	758

(Friday) was warm and humid, with relative humidity between 42 and 55 percent. HI varied between 97 and 101 degrees F (see Table 1). Skies were partly cloudy and winds were calm. After a cold front moved through during the night, Saturday was less humid (29–31% RH) and cooler, with HI ranging from 80 to 81 degrees F in the morning session. HI was between 85 and 88 degrees F during the afternoon session. Moderate winds, gusting strongly enough to cause the video camera to vibrate on the tripod, were observed during the Saturday morning session. Skies were clear and sunny throughout the day. The intensity and angle of the sun caused backlit conditions and glare, both of which tended to obscure window position. In response, field staff adjusted the video camera to minimize the negative effects of strong sunshine on data collection.

Videotaping was performed mainly during afternoon and early evening hours, when HI values were likely to be highest. Vehicles used for window position determination were videotaped between the hours of 11 am–2 pm and 4 pm–7 pm.

Monitoring Equipment

An 8-mm Sony Handycam video camera recorder (Model CCD-TR517, Sony Corp., Tokyo, Japan) mounted on a tripod was used to videotape all traffic monitored during this study. This video camera has an optical zoom capability of 20× and a digital zoom capability of 200×, enabling the technician to record close-up images of the vehicles. An extended-duty battery (Model NP-F750, Sony Corp.) was installed in the camera to ensure continuous operation during the taping sessions. The sessions were recorded on Standard 8 videocassettes and copied to VHS videotapes for playback and data analysis. The VHS tapes were reviewed on a combination television/videocassette recorder unit (Model VV-2000, Matsushita Electric Corp. of America, Secaucus, NJ). Temperature and relative humidity were measured during the taping sessions with a digital thermometer-hygrometer (Cat. No. 63-1013, RadioShack Corp., Fort Worth, TX). The hygrometer was placed in the shade to improve measurement accuracy.

Monitoring Procedures

Videotaping was performed over a two-day period. Researchers conducted a total of five taping sessions at various HI and traffic flow speed conditions, with each session lasting between 19 and 53 minutes. Field staff set up the video camera on a tripod and adjusted the camera to provide a clear view of all windows in each vehicle. Prior field testing indicated that a single, properly positioned camera could capture the required information for a high percentage of vehicles, reducing the need for placement of multiple cameras and later simultaneous review of several videotapes. The zoom function on the video camera was used to obtain close-up images of the vehicle windows, with the result that some vehicles briefly passed out of the field of view after displaying one side to the camera. When the vehicles returned into view, the windows on the opposite side of the vehicle were visible. Field staff positioned the video camera to achieve a camera angle maximizing the reflection of light from the window surfaces. This approach aided researchers when they later viewed the videotape to determine whether windows were closed (reflective) or open (non-reflective). A time/date stamp was included on all tapes.

To determine the flow speed of traffic during the taping session, researchers timed the speed of a randomly selected vehicle on the main roadway over a measured distance every few minutes. At the arterial road sites, field staff observed some drivers increasing or decreasing their speed as they approached the intersection, depending on traffic conditions and the status of the traffic signal. This tendency has the effect of artificially increasing the range of vehicle speeds recorded at those sites. In addition, field staff recorded temperature and humidity values at approximately 15-minute intervals.

Inspection of Videos and Data Entry

Researchers inspected the video images of vehicles passing through the camera's field of view and attempted to enter pertinent data for each vehicle into a spreadsheet. A single individual reviewed all videotapes to provide consistency in recording vehicle information. Recorded data included (1) location, date, and time; (2) vehicle type and color; (3) total

number of windows in the vehicle; (4) numbers of windows completely open, partially open, and closed; (5) presence of a sunroof or convertible top and its position (open/closed); and (6) the number of occupants in each vehicle. If one or more pieces of information could not be determined from the videotape within a reasonable period, researchers entered codes into the database listing the information as uncertain and describing the reason for the uncertainty. To minimize interpreter bias, the researcher coded as "uncertain" any vehicle characteristics that were ambiguous due to unclear video images. Statistical analyses did not include vehicles with uncertain window or sunroof positions. Processing the data for each vehicle generally required 30 to 90 seconds, including examining and reexamining the video and entering the data.

Each vehicle passing the camera during the review time period was included in the database, including cases in which no window position information could be determined. Researchers continued to process the vehicle data for a particular videotaping session until at least 150 valid cases had been recorded. Valid cases were defined as vehicles for which researchers could determine the position of every window and the sunroof, regardless of whether or not the number of occupants could be determined. The total

Table 2. Frequency distributions for selected variables relating to monitoring conditions.

Variable	Category	Number of valid cases	Percent of total valid cases	Percent of vehicles in category with one or more open windows[a]
Location	Katy Mills	453	59.8	15.7
	Katyland Drive	153	20.2	25.5
	Woodlands	152	20.1	19.7
Date	9/15/00 (Friday)	457	60.3	17.9
	9/16/00 (Saturday)	301	39.7	19.3
Time (total taping duration in this clock hour; min)	1100–1159 (30)	215	28.4	16.7
	1200–1259 (14)	86	11.3	7.0
	1300–1359 (27)	152	20.1	19.7
	1600–1659 (46)	122	16.1	27.1
	1700–1759 (8)	31	4.1	19.4
	1800–1859 (25)	152	20.1	19.1
Temperature [°F]	81	124	16.4	17.7
	82	25	3.3	24.0
	88	60	7.9	23.3
	90	92	12.1	17.4
	91	207	27.3	11.1
	93	145	19.1	23.5
	95	105	13.9	23.8
Relative humidity [%]	28	92	12.1	17.4
	29	85	11.2	23.5
	30	76	10.0	19.7
	31	48	6.3	14.6
	42	31	4.1	32.3
	43	122	16.1	23.8
	47	97	12.8	20.6
	50	55	7.3	16.4
	55	152	20.1	9.2
HI [°F]	80	149	19.7	18.8
	85	60	7.9	23.3
	87	92	12.1	17.4
	97	103	13.6	22.3
	99	249	32.8	13.7
	100	31	4.1	32.3
	101	74	9.8	20.2
Vehicle speed [miles/h]	30–39	118	15.6	26.3
	40–49	167	22.0	21.0
	50–59	29	3.8	10.3
	60–69	292	38.5	15.1
	70–79	152	20.1	17.8

[a]Includes windows, sunroofs, and convertible tops.

Table 3. Frequency distributions for selected variables relating to vehicle characteristics.

Variable	Category	Number of valid cases	Percent of total valid cases	Percent of vehicles in category with one or more open windows[a]
Vehicle type	Passenger car (hardtop)	395	52.1	20.0
	Minivan/passenger van	55	7.3	16.4
	Sport utility vehicle	160	21.1	10.6
	Pickup truck	127	16.8	22.1
	Commercial truck	8	1.1	25.0
	Convertible	13	1.7	38.5
Window configuration	2 windows	234	30.9	22.2
	2 windows + sunroof	14	1.8	21.4
	2 windows + convertible top	9	1.2	22.2
	3 windows	14	1.8	35.7
	4 windows	444	58.6	14.4
	4 windows + sunroof	37	4.9	29.7
	4 windows + convertible top	4	0.5	75.0
	Other	2	0.3	0
Color	White	180	23.7	17.2
	Black	210	27.7	22.9
	Silver/gray	139	18.3	14.4
	Red	105	13.9	15.2
	Blue	62	8.2	16.1
	Green	39	5.1	25.6
	Brown	3	0.4	33.3
	Tan	16	2.1	25.0
	Yellow	1	0.1	0
	Other	3	0.4	0

[a]Includes windows, sunroofs, and convertible tops.

numbers of vehicles processed and included in the database during each taping session are presented in Table 1. Quality assurance procedures performed on the database prior to statistical analysis included searching for the presence of anomalous values; verifying that the number of open, partially open, and closed windows on each vehicle was consistent with the total number of vehicle windows; checking that weather and traffic speed data were properly associated with each vehicle; and reviewing the videotapes as necessary to resolve apparent discrepancies.

Results

Construction of Database for Statistical Analysis

Analysts initially constructed a database listing data on 868 vehicles monitored during the five sessions listed in Table 1. The database contained a variety of parameters relating to monitoring conditions such as location, date, time of day, temperature, relative humidity, and HI. Data specific to each vehicle included vehicle type (e.g., minivan), color, number of occupants, number of windows fully open, number of windows partially open, number of windows closed, and number of windows not visible. The database also included data on the position of sunroofs (open/closed) and convertible tops (up/down). Prior to analyzing the database, analysts identified 107 vehicles (12 percent) in which one or more windows were not visible because of sun angle, another vehicle, or attached visor. These vehicles were omitted from subsequent analyses. Three motorcycles were also omitted. The remaining 758 vehicles were used as the master database for the statistical analyses that follow.

Table 2 presents frequency distributions for selected parameters relating to monitoring conditions based on the 758 vehicles in the master database. Sixty percent of the vehicles were videotaped at the Katy Mills interstate location, with the remaining vehicles evenly split between the two arterial road locations (Katyland Drive and Woodlands). Sixty percent of the vehicles were monitored on Friday, September 15. The remaining vehicles were monitored on Saturday, September 16. Of the six clock hours represented in the database, the clock hour beginning at 1100 (i.e., 1100 to 1159) had the largest number of vehicles (215) in 30 total minutes of taping and the clock hour beginning at 1700 had the smallest number (31) in 8 total minutes of taping. HI ranges of 80, 85 to 87, and 97 to 101 degrees F. were associated with 149, 152, and 457 vehicles, respectively. Approximately 38 percent of the vehicle speeds were between 30 and 49 mph; the remaining 62 percent were between 50 and 79 mph with 39 percent occurring in the interval of 60 to 69 mph.

Table 4. Frequency distributions for specific combinations of vehicle type and window configuration.

Category		Number of valid cases	Percentage of total valid cases	Percent of vehicles in category with one or more open windows[a]	Percent of vehicles in category with open sunroof or convertible top
Vehicle type	Window configuration				
Passenger car (hardtop)	2 windows	62	8.2	29.0	–
	2 windows + sunroof	13	1.7	23.1	15.4
	4 windows	288	38.0	16.7	–
	4 windows + sunroof	32	4.2	31.3	21.9
Minivan/passenger van	2 windows	45	5.9	15.6	–
	3 windows	7	0.9	28.6	–
	4 windows	2	0.3	0	–
	Other	1	0.1	0	–
Sport utility vehicle	2 windows	7	0.9	14.3	–
	2 windows + sunroof	1	0.1	0	0
	4 windows	147	19.4	10.2	–
	4 windows + sunroof	5	0.7	20.0	20.0
Pickup truck	2 windows	112	14.8	21.4	–
	3 windows	7	0.9	14.3	–
	4 windows	7	0.9	0	–
	Other	1	0.1	42.9	–
Commercial truck	2 windows	8	1.1	25.0	–
Convertible	2 windows+convertible top	9	1.2	22.2	22.2
	4 windows+convertible top	4	0.5	75.0	75.0
All vehicles		758	100.0	18.5	–

[a]Includes windows, sunroofs, and convertible tops.

Table 3 presents frequency distributions for selected parameters relating to vehicle characteristics. Of the seven vehicle types appearing in the database, passenger cars with hardtops occur most frequently (52.1 percent) and commercial trucks least frequently (1.1 percent). With respect to the seven window configurations listed in Table 3, vehicles with four windows occur most frequently (58.6 percent) followed by vehicles with two windows (30.9 percent). Note that these categories do not include vehicles with sunroofs or convertible tops, which are classified separately.

Although vehicle color was included in the database primarily for quality assurance purposes, subsequent statistical analyses detected a weak correlation between color and window position. Table 3 provides frequency distributions for 10 color categories. Note that the colors are characterized by hue only. In hindsight, color should also have been characterized by shade (e.g., light, medium, dark), as shade is more likely to affect internal vehicle temperature than hue.

Table 3 does not provide a frequency distribution for number of vehicle occupants, because this statistic was

Table 5. Frequency distributions for specific combinations of HI and vehicle speed.

Category		Number of valid cases	Percentage of total valid cases	Percent of vehicles in category with one or more open windows[a]
HI [°F]	Vehicle speed [miles/h]			
80	60–69	79	10.4	21.5
	70–79	70	9.2	15.7
85	40–49	60	7.9	23.3
87	40–49	92	12.1	17.4
97	30–39	48	6.3	29.2
	60–69	55	7.3	16.4
99	50–59	9	1.2	0.0
	60–69	158	20.8	11.4
	70–79	82	10.8	19.5
100	30–39	16	2.1	31.3
	40–49	15	2.0	33.3
101	30–39	54	7.1	22.2
	50–59	20	2.6	15.0
All vehicles		758	100.0	18.5

[a]Includes windows, sunroofs, and convertible tops.

Table 6. Frequency distributions for specific combinations of location, date, and time of day.

Category			Number of valid cases	Percentage of total valid cases	Mean speed [miles/h]	Mean HI [°F]	Percent of vehicles in category with one or more open windows[a]
Location	Date	Clock hour					
Katy Mills	9/15/00	1100–1159	66	8.7	66	100	12.1
		1200–1259	86	11.3	66	100	7.0
		1800–1859	152	20.1	67	99	19.1
	9/16/00	1100–1159	149	19.7	70	80	18.8
Katyland Drive	9/15/00	1600–1659	122	16.1	40	100	27.1
		1700–1759	31	4.1	39	101	19.4
Woodlands	9/16/00	1300–1359	152	20.1	47	87	19.7
All vehicles			758	100.0	58	93	18.5

[a]Includes windows, sunroofs, and convertible tops.

determined for only 170 (22 percent) of the 758 vehicles in the master database. In reviewing the videotapes, researchers found that it was difficult to accurately determine the number of passengers in many of the vehicles, because window reflection greatly limits visibility into the interior of the vehicle. Although reflection of light from window surfaces is quite important for determining window position, at the same time it hinders determination of the number of vehicle occupants. Aside from reflectivity, other factors that limited researchers' view of vehicle interiors were tinted windows and dark vehicle interiors. Researchers had particular difficulty in seeing rear seat occupants.

Each vehicle in the master database was assigned a value for the variable OPEN in which OPEN=1 indicated that one or more windows were fully or partially open, a sunroof was open, and/or a convertible top was down. OPEN=0 indicated the vehicle was completely closed with respect to windows, sunroofs, and convertible tops. Hereafter, vehicles with OPEN values equal to 1 and 0 will be referred to as "open vehicles" and "closed vehicles", respectively. The far-right columns in Tables 2 and 3 indicate the percentage of open vehicles in each category. The overall rate (n=758) for this statistic was 18.5 percent.

Table 4 provides frequency distributions and open vehicle statistics for categories defined by vehicle type and window configuration. Table 5 provides similar results for categories defined by HI and vehicle speed. Results for categories defined by location and date are presented in Table 6.

Researchers reviewed the results in Tables 2 through 6 with the goal of identifying variable categories associated with open-vehicle percentages that were noticeably smaller or larger than the average value for all vehicles (18.5 percent). Based on this review, researchers defined the 16 variables in Table 7 as candidate predictor variables for stepwise linear regression (SLR) analyses in which OPEN

Table 7. Variables created for stepwise linear regression analyses.

Variable	Conditions when variable equals 1 (variable equals 0, otherwise)	Percent of vehicles with one or more open windows[a]	
		When variable equals 1	When variable equals 0
BLACK	Vehicle color = black	22.9	16.8
CONVERT	Convertible	38.5	18.1
EARTHTONE	Vehicle color is green, brown, or tan	25.9	17.9
KATYLAND	Location = Katyland Drive	25.5	16.7
KATYMILLS	Location = Katy Mills	15.7	22.6
SATURDAY	Date = 9/16/00 (Saturday)	19.3	17.9
SILVER	Vehicle color is silver or gray	14.4	19.4
SLOWHOT	Speed <50 miles/h and HI >99.9°F	25.9	17.5
SPEEDLT50	Speed <50	23.2	15.6
SUV	Sport utility vehicle	10.6	20.6
HIGT99	HI >99.9°F	23.8	17.6
TIME12	Time between 1200 and 1259 h	7.0	19.9
TIME16	Time between 1600 and 1659 h	27.1	16.8
VEHWSUNROOF	Vehicle with sunroof	27.5	17.8
WHITE	Vehicle color is white	17.2	18.9
WIN3	Vehicle has three windows	35.7	18.2

[a]Includes windows, sunroofs, and convertible tops.

Table 8. Results of SLR analyses by vehicle type when dependent variable = OPEN using candidate predictor variables in Table 7 as appropriate.

Vehicle types included in analysis	Sample size (n)	Regression results[a]		
		Variables included in regression equation	Regression coefficient	Cumulative R^2
All vehicles	758	Constant	0.184	0.0000
		TIME12	− 0.115	0.0112
		SUV	− 0.101	0.0222
		BLACK	0.077	0.0290
		TIME16	0.083	0.0350
Passenger car (hard top)	395	Constant	0.172	0.0000
		BLACK	0.114	0.0152
Minivan/passenger van	55	Constant	0.104	0.0000
		SLOWHOT	0.467	0.1772
SUV	160	Constant	0.049	0.0000
		SPEEDLT50	0.159	0.0607
Pickup truck	127	Constant	0.255	0.0000
		TIME12	− 0.255	0.0437
Commercial truck	8	Constant	0.250	0.0000
Convertible	13	Constant	0.384	0.0000

[a]Dependent variable is OPEN for all analyses. OPEN equals 1 when one or more windows, a sunroof, and/or a convertible top is open. OPEN equals 0, otherwise.

was the dependent variable. Table 8 provides results of the SLR analyses for all vehicles and for six subsets of vehicles based on vehicle type. Table 9 presents SLR results for vehicles grouped by videotaping location.

Each SLR analysis used all variables in Table 7 as candidate predictor variables, with the exception of any variable that had the same value for all vehicles in the data classification. In reviewing the results of each analysis, researchers checked appropriate diagnostics provided in the SLR outputs (e.g., the variance inflation factor) to determine whether the pool of candidate variables exhibited significant collinearity. In performing the SLR analyses, analysts specified p-to-enter and p-to-exit values of 0.05 for adding and removing variables, consistent with recommendations by Draper and Smith (1981).

The first listing in Table 8 provides results for a SLR analysis performed on all 758 vehicles in the master database. The four parameters selected into the regression equation are listed according to the order in which they were selected. The table lists the regression coefficient of each parameter and indicates the cumulative R^2 value. Definitions of the parameters can be found in Table 7. The resulting regression equation can be expressed as

$$\begin{aligned} \text{OPEN} = {} & 0.184-(0.115)(\text{TIME12})-(0.101)(\text{SUV}) \\ & +(0.077)(\text{BLACK})+(0.083)(\text{TIME16}) \\ & +\text{e} \end{aligned} \tag{2}$$

in which e is the residual term.

Table 9. Results of SLR analyses by location when dependent variable = OPEN using candidate predictor variables in Table 7 as appropriate.

Location	Sample size (n)	Regression results[a]		
		Variables included in regression equation	Regression coefficient	Cumulative R^2
Katy Mills	453	Constant	0.209	0.0000
		SUV	− 0.140	0.0250
		TIME12	− 0.110	0.0390
Katyland Drive	153	Constant	0.281	0.0000
		SILVER	− 0.226	0.0279
Woodlands	152	Constant	0.117	0.0000
		BLACK	0.255	0.0572
		EARTHTONE	0.241	0.0869

[a]Dependent variable is OPEN for all analyses. OPEN equals 1 when one or more windows, a sunroof, and/or a convertible top is open. OPEN equals 0, otherwise.

The sign of each regression coefficient provides a directional indicator of the associated variable's effect on OPEN, with the caveat that the value of the regression coefficient may vary according to the other variables included in the regression equation. Factors tending to *decrease* OPEN when all vehicles are considered (i.e., n=758) include TIME12 (time between 1200 and 1259) and SUV (vehicle is a sport utility vehicle). Factors tending to *increase* OPEN include BLACK (vehicle color is black) and TIME16 (time between 1600 and 1659). Note that the regression model based on these four variables explains less than 4 percent of the total variability in the OPEN values (R^2=0.0350). While the effect of each of the four variables on OPEN is statistically significant, the regression equation does not provide a very powerful model for predicting whether a particular vehicle in the database will be open or closed.

Table 8 also provides results of SLR analyses performed on subsets of vehicles defined by vehicle type. The regression equation for passenger car (hardtop) includes only one variable (BLACK), which has a positive coefficient. SLOWHOT (vehicle speed is less than 50 mph and HI is greater than 99.9 degrees F) is the only variable appearing in the regression equation for minivan/passenger vans; the variable has a positive coefficient. The R^2 value for this equation (0.1772) is the largest value listed in Table 8.

The regression equation for sport utility vehicles also includes a single variable (SPEEDLT50). The regression coefficient is positive, indicating that these vehicles tend to open windows when speed is less than 50 mph. The effect is quite weak, however, as the R^2 value is only 0.0607. The R^2 value for pickup trucks is even lower (0.0437). The regression equation for pickup trucks includes TIME12 with a negative coefficient. No predictor variables were identified by the SLR analyses performed on commercial trucks or convertibles, possibly because of the small sample sizes available for these two vehicle types.

Table 9 provides results of SLR analyses specific to videotaping location. The regression equation for Katy Mills includes the SUV and TIME12 variables, both with negative coefficients. The Katyland Drive equation includes a single variable (SILVER=vehicle color is silver or gray). The Woodlands equation contains two variables (BLACK and EARTHTONE), both with positive coefficients. The R^2 values for all three regression equations are low, ranging from 0.0250 (Katy Mills) to 0.0869 (Woodlands).

Although none of the diagnostic values suggested that collinearity affected the SLR results presented above, it should be noted that the KATYLAND variable exhibited relative high correlation with several other variables (including KATYMILLS, SLOWHOT, SPEEDLT50, HIGT99, and TIME16). To evaluate the potential effect of KATYLAND on the SLR results, researchers repeated the SLR analyses with this variable excluded from the pool of candidate variables. There was no change in the results. Similar analyses were performed in which other suspect variables were omitted from the SLR analyses with no change in results.

Overall, the SLR results suggest that the probability of a vehicle in the master database being "open" is weakly affected by time of day, vehicle type, vehicle color, vehicle speed, and HI. It is important to note, however, that the predictor variables selected for inclusion in the regression equation vary with vehicle type and videotaping location.

Discussion and recommendations

The vehicles included in the pilot study represent a set of special conditions that should be carefully considered in evaluating the study results. The vehicles were videotaped at locations on the perimeter of the Harris County in or near areas not subject to I&M. Consequently, the proportion of older vehicles with poorly maintained or non-operating air conditioners was likely higher than would have been observed in central portions of Harris County where vehicles are subject to I&M.

HI varied from 80 to 101 degrees F during the videotaping sessions. It would be expected that most drivers with working air conditioning systems would have the air conditioner on and windows closed under these conditions. The exception would be cases in which the driver had windows open to cool a vehicle during the first few minutes of driving. Such cases may have occurred more frequently at the Katyland Drive site where taping occurred late in the afternoon in an area near schools and light industry.

We would expect windows to be open more frequently when HI falls between 65 and 75 degrees, F. As the HI falls below 65 degrees F, we would expect windows to be closed more frequently as drivers begin to use their heaters. To test these assumptions, researchers plan to conduct a follow-up study during 2001 in which vehicles will be videotaped under a full range of HI values.

The database includes vehicle speeds between 30 and 74 mph. In general, we would expect passengers to open windows at lower speeds because of the reduced flow-through ventilation. They would tend to close windows at higher speeds to reduce wind noise and buffeting. The results of this pilot study weakly support these expectations, as open windows showed a slight tendency to occur more frequently when speeds fell within the 30 to 49 mph range, particularly when HI exceeded 99.9 degrees F and the vehicle was a minivan or passenger van. In the planned follow-up study, researchers will attempt to obtain window position data for vehicles moving at speeds below 30 mph.

Field staff noticed a number of drivers knocking ash from cigarettes through a partially open driver's window. In other

cases, field staff observed drivers smoking in vehicles with a partially open driver's window, possibly to allow secondary smoke to escape. This anecdotal evidence indicates that vehicles containing a smoker may have a higher proportion of partially open windows than the general population, especially under conditions expected to favor the use of air conditioning (e.g., high HI).

One reason for uncertainty in determining window and sunroof positions was the presence of visors or shields near the edge of the windows and sunroofs. These structures are designed to provide protection from wind at high speeds. On the videotapes, the effect of the visors is to obscure a portion of the window or sunroof from view, preventing researchers from determining whether the window or sunroof is completely closed or partially open. Fully open windows and sunroofs are not affected by the visors. Therefore, vehicles excluded from the statistical analysis because of window or sunroof visors are likely to have a higher proportion of closed and partially open windows than vehicles included as valid cases.

In this article, we have shown how data on factors affecting vehicle window position can be acquired through a relatively simple experimental protocol using a single video camera. In the planned follow-up study, we intend to address some of the limitations of the database obtained during the pilot study, particularly the lack of data for lower ranges of speed and HI. We will also attempt to acquire better data for determining the effects of vehicle occupancy and color, two additional factors that may influence window position.

Another non-meteorological factor that may affect window position is personal safety. When driving through a neighborhood perceived as dangerous, occupants may close vehicle windows to limit access to the vehicle, even when weather conditions are conducive to open windows. The videotaping sites in this study were chosen to avoid such dangerous areas.

The principal advantages of the video taping approach described in this article are that (1) the method places little or no burden on the people being monitored and (2) it can acquire a large sample of representative vehicle data with a relatively small expenditure of resources. Perhaps the greatest deficiency of the video taping approach is that it is incapable of determining the on/off status of air conditioners and vents in passing vehicles.

Although limited literature data are available on vehicle window position, some general comparisons may be made between the present study and studies investigating the use of vehicle air conditioning. An article by Levine et al. (2000) describes a study that recorded vehicle air conditioner compressor usage during summer 1997 in the Sacramento, CA area. Ten vehicles with functioning, manually-operated air conditioning systems were equipped with instruments to collect data on the on/off status of the air conditioner compressor while driving. Vehicle window position was not reported. The authors found that the compressor was in use at some point during 65% to 90% of the trips occurring between 80 and 95 degrees F, corresponding to the range of temperatures measured during the present study in Houston. In other words, between 10% and 35% of these trips did not include air conditioning use, a range that is in broad agreement with the overall open-vehicle rate of 18.5% observed in Houston. Additional information would be required to apply the results of the Sacramento study to a larger vehicle population, such as the percentage of vehicles in the population with non-functioning air conditioners; the percentage of vehicles without air conditioning units; and the percentage of trips including both air conditioner use and open vehicle windows.

Other methods of acquiring usable air conditioning data include (1) placing camera or videotape systems in the passenger compartments of a large number of vehicles and/or (2) equipping subjects riding in these vehicles with real-time paper or audio diaries. An article by Johnson et al. (1992) describes a number of studies that have used real-time paper and audio diaries to collect time/activity data in various microenvironments. A more recent article by Johnson et al. (2001) evaluates a number of new technologies that may be useful in collecting time/activity data in both vehicle and non-vehicle microenvironments. The article includes an in-depth test of a photo-diary system that could be used to photograph the air conditioning control panel of a motor vehicle at one-minute intervals, providing time-correlated data on air conditioner settings, recirculation status of the air inlet damper, and other information. Information of this type can be used to improve estimates of air exchange rate and exposure of vehicle occupants to air pollutants.

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