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**SIMULTANEOUS GRAVIMETRIC AND LIGHT SCATTER MEASUREMENTS
OF SUMMER AND WINTER AEROSOLS INSIDE A CAR TUNNEL**

by

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Summary.

In this work, measurements have been made of the summer, fall and winter aerosol levels inside a busy car tunnel. The main purpose of the study has been to compare the performance of an optical (light scatter) aerosol monitor, permanently installed in the tunnel, with that of a portable gravimetric monitor set to sample the standardized aerosol fraction PM₁₀. Some gravimetric measurements of the finer particle fraction PM_{2.5} have also been included.

The results of the comparison indicate that the optical monitor, with an appropriate calibration factor incorporated, provides time averaged measurement values that closely correspond to similarly averaged PM₁₀ values for aerosol concentrations ranging from 50 to 300 µg/m³. As long as the tunnel pavement is dry, the same calibration factor appears to be appropriate for both summer and winter operation of the optical monitor, even though the winter aerosol is dominated by coarse particles caused by the grinding action of studded snow tires.

On a rainy day, with the tunnel pavement wet, the optical monitor overestimated the PM₁₀ level by about 40%, possibly as a result of spray droplet formation. This hardly warrants a recalibration of the monitor, since the aerosol levels associated with such rainy days generally are too low to be of any concern. The supplementary series of PM_{2.5} measurements indicate that the optical monitor at hand cannot be calibrated for the monitoring of that particular aerosol fraction on a year-round basis.

An automatic traffic monitoring system in the tunnel provided the means for comparing time averaged tunnel aerosol levels with traffic rates. The vehicles were sorted into two size classes with lengths smaller and larger than about 5.5 m. The resulting data suggest that at summertime, the particle emission of the average small vehicle relative to that of the average large one, is only of the order 1%. For the coarse particles of the winter aerosol, the data suggest a relative small vehicle contribution of the order 5%. These estimates, if proven valid, have the implication that both summer and winter traffic aerosols in the area of the study are dominated by emissions from heavy diesel powered vehicles rather than ordinary passenger cars.

1. Introduction

The Norwegian Public Road Administration, Hordaland Section, operates an aerosol monitoring station inside the Nygaard motor vehicle tunnel within the city of Bergen. The monitoring site is located in the west-bound tube of the tunnel, which opened for traffic in 1999. The tube is a three lane, 860 m tunnel leading traffic out of the downtown area at a typical rate of about 12500 vehicles per day on week-days. The west-bound tube exit is surrounded by a residential neighborhood. For this reason a large, electrostatic particle filter has been installed inside the tube to prevent escaping aerosols from reaching concentrations that may have an unacceptable effect on the air quality outside. The main purpose of the aerosol monitoring station is to provide the air quality information needed for automatic operation of this tunnel filter when, and only when, it is required.

The permanent tunnel aerosol monitor is an optical device designed for extended, unattended use in remote locations^(a). Its operation is based on the light scattering properties of airborne particles. An infrared light source inside the unit illuminates the air space outside, and a detector senses the light scattered back into the instrument at some fixed angle to the exit beam. The component geometry defines an active scattering region some 0.5 m outside the instrument casing.

Each of two signal outputs from the monitor may be furnished with a calibration factor for converting light scatter intensity to some measure of aerosol concentration. Prior to this study the instrument supplier had calibrated the unit so as to provide readings approximating the aerosol fraction designated PM₁₀. By definition, PM₁₀ is the mass concentration, in units of $\mu\text{g}/\text{m}^3$, of all suspended particles of aerodynamic diameter less than 10 μm . The reason for emphasizing this aerosol fraction is that many countries, including Norway, use PM₁₀ as a basis for implementing air quality standards that are to protect the general public from excessive particle exposure⁽¹⁾.

Given the definition of PM₁₀, the use of light scatter instrumentation for its measurement may not be the obvious choice, since no unique,

(a) Visibility monitor, Mod. VISIC 610-T, manufactured by SICK AG, Waldkirch, Germany.

generally valid relationship exists between light scatter characteristics and mass concentrations of aerosols. The amount of light scattered from a collection of airborne particles will depend on a number of factors that characterize the individual particles, the most important being size, shape, and complex index of refraction⁽²⁾. None of these factors relate directly to particle mass. The primary reason for the popularity of light scatter instruments as aerosol pollution monitors, then, is not so much their potential for providing mass measurements, as it is their superiority to gravitational instrumentation in being adaptable for remote, automatic operation.

Whether a given light scatter instrument is appropriate for monitoring PM₁₀ will depend not only on its design and state of calibration, but also to a large extent on the nature of the aerosol at the given monitoring site. The matter is further complicated by the fact that the characteristics of such an aerosol are likely to vary both on a day-to-day and a season-to-season basis. This state of affairs strongly points to the need for comparing the performance of the light scatter monitor in the Nygaard tunnel with genuine PM₁₀ mass measurements at the same site. Series of such parallel measurements were made on a number of occasions during the latter half of 1999, the results of which are reported here.

2. Experimental arrangement.

The performance of the Nygaard tunnel monitoring system was evaluated using a portable aerosol mass monitor^(b) having an extensive record of service at this university^(3,4). Identical type instruments have been used by a number of investigators throughout the world for both indoor and outdoor studies^(5,6,7,8,9). The monitor contains a pump that draws a carefully controlled stream of ambient air through the unit. A size selective impactor on the inlet prevents particles of aerodynamic diameter larger than a selected value (for this study either 2.5 μm or 10 μm) from following the air stream into the instrument. By the use of electrostatic effects, the remaining particles are made to deposit on a quartz crystal which provides for real time registration of the accumulating mass. The signal representing particle mass is presented on

(b) Piezobalance Aerosol Monitor, Mod. 3500, manufactured by TSI Inc., Minnesota, USA.

a display for manual recordkeeping and subsequent computational treatment. Knowing the sampling period and the air flow, the mass concentration of the selected aerosol size fraction (PM_{2.5} or PM₁₀) may be calculated in units of $\mu\text{g}/\text{m}^3$.

With a sampling period of four minutes, the resolution of the mass monitor is about $2 \mu\text{g}/\text{m}^3$. The measurement accuracy depends on the type of aerosol being monitored. Performance evaluations of identical units using gravimetric membrane filter techniques have demonstrated accuracies within $\pm 15\%$ for a variety of common particle types^(5,10). In several such tests, investigators have found that instruments of the noted type show less variation during simultaneous measurements than other methods evaluated, including the membrane filter technique itself⁽¹¹⁾.

The permanent optical monitor in the Nygaard tunnel is attached to a vertical steel post at a place where the three-lane tunnel tube divides into two separate exit tubes. The monitor is mounted at a height of about 4 m, near the tunnel ceiling. To allow the portable mass monitor to be operated near by, a scaffold was erected adjacent to the vertical mounting post. This way, an operator could perform the mass measurements at the same height as, and about 1 m to the side of the sensing zone of the optical monitor.

The optical unit computes a 250 second running average of the calibrated light scatter signal and stores the outcome in a dedicated computer at defined intervals. In this study these intervals were set to either two or four minutes. Thus, the optical monitor continuously provided 30, respectively 15 aerosol measurements per hour, each representing a sampling period of nearly four minutes. To match this, four-minute sampling periods were chosen for the portable mass monitor as well. In the latter case at most five such samplings could be made per hour, however, due to operational constraints. In what follows, the basic four-minute registrations provided by the two monitors will be denoted *primary measurements*, to distinguish these from various time averaged results to be presented.

On the first two days of measurements, no attempts were made at synchronizing the parallel series of primary measurements. Consequently, the sampling periods of the primary measurements that subsequently were

compared may have been offset in time by as much as two minutes. Later in the study a synchronization procedure was implemented, limiting this possible sampling time offset to about 20 seconds. The main reason for improving the synchronization in this manner was early observations that some heavy vehicles emitted particles at such rates that their passage alone could cause the tunnel aerosol concentration to increase markedly on a time scale of less than a minute.

Simultaneous mass and light scatter measurements were made on six days during the period September-December 1999. The days were separated in time so that summer-, fall- and winter conditions were allotted two days each. Each day, two 1-2 hour visits were made to the tunnel monitoring site, one at midday and a second one in the afternoon covering the rush hour. The environmental conditions inside and outside the tunnel on these six days are specified in table 1.

Day no. Time of year	Weather	Tunnel air		Pavement	Type of vehicle tires
		°C	RH %		
day 1: mid-september	diminishing rain light breeze, 17°C	15-16	80-81	nearly dry	ordinary
day 2: mid-september	partly cloudy light breeze, 18°C	17-18	74-75	dry	" "
day 3: mid-november	clear, calm air, 4°C	6	56	dry	Mostly ordinary, some snow tires
day 4: mid-november	rain, windy, 8°C	9	83	wet	" "
day 5: mid-december	clear, light breeze, -1°C	1	50	dry	snow tires
day 6: mid-december	clear, calm air, -1°C	0-2	43-47	dry	" "

Table 1. Weather and tunnel conditions on the six days of simultaneous measurements in the Nygaard tunnel. The days in September, November and December represent summer, fall and winter conditions, respectively. The type of vehicle tires in use on these occasions is indicated.

The table also lists the type of tires in use on these days. In the summer (days 1 and 2), all vehicles were equipped with ordinary tires. On days 3 and 4, which were chosen to correspond with the onset of the winter season, some vehicles carried snow tires. On days 5 and 6 winter conditions had prevailed for some time, implying that nearly all vehicles were equipped with snow tires. According to surveys made at the time, 30-40% of these snow tires were studded tires.

The traffic in the Nygaard tunnel is monitored on a continuous basis by a system of automatic sensors. These sensors distinguish between different size vehicles, one such distinguishing parameter being a vehicle length of about 5.5 m. Most vehicles smaller than this measure are ordinary, gasoline driven passenger cars, whereas the longer ones are mostly heavier, diesel driven vehicles (vans, trucks, trailers, etc.). Each day of the study, records were secured of the hourly traffic rates for these two categories of vehicles.

3. Results

For the purpose of illustration, the progression of all parallel primary measurements on each of three selected days of the study is presented in figures 1, 2 and 3. The days chosen (days 2, 4 and 5) correspond to summer, fall and winter conditions, respectively. The diagrams show both the PM10 data and the less frequent PM2.5 data from the portable monitor.

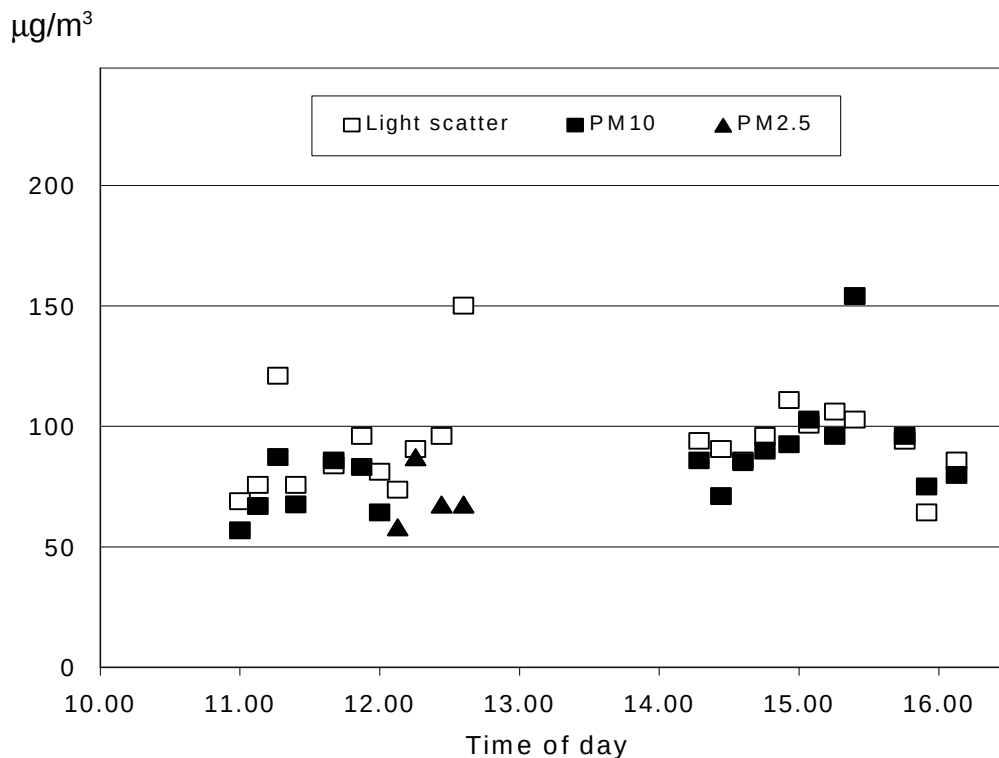


Figure 1: Progression of parallel primary measurements on day 2 (summer).

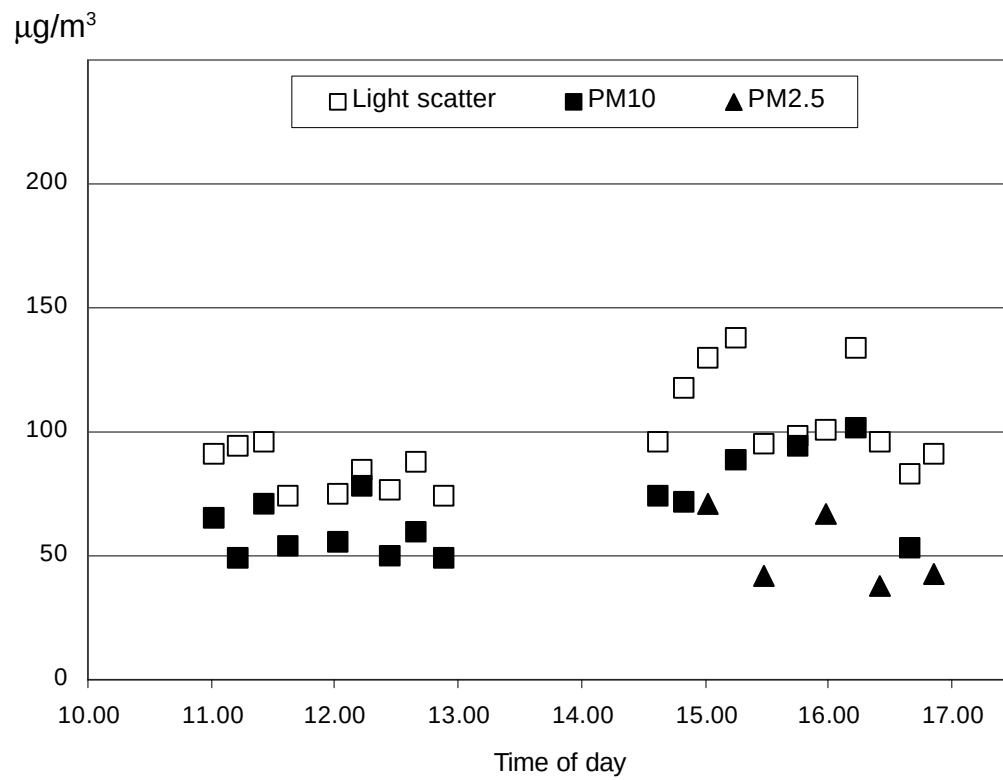


Figure 2: Progression of parallel primary measurements on day 4 (wet pavement).

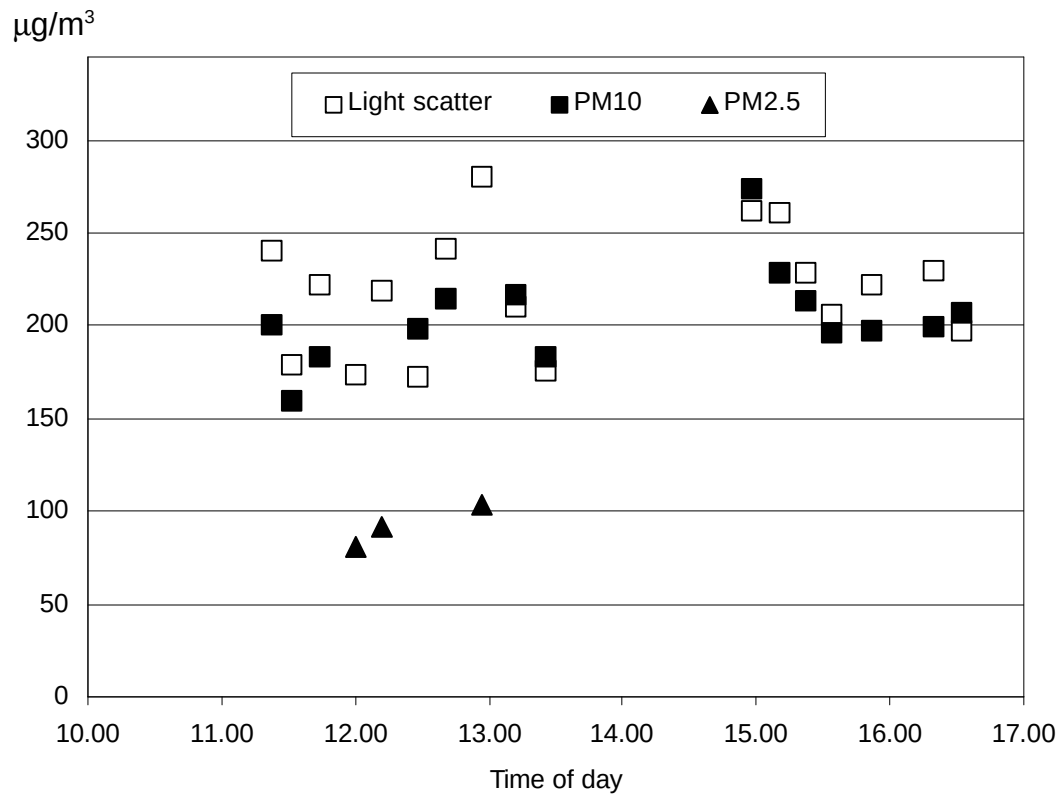


Figure 3: Progression of parallel primary measurements on day 5 (winter).

Figure 4 is a scatter diagram of all pairs of PM10-related primary measurements obtained in the study. In this diagram the data from day 4 have been treated separately for reasons to be explained below.

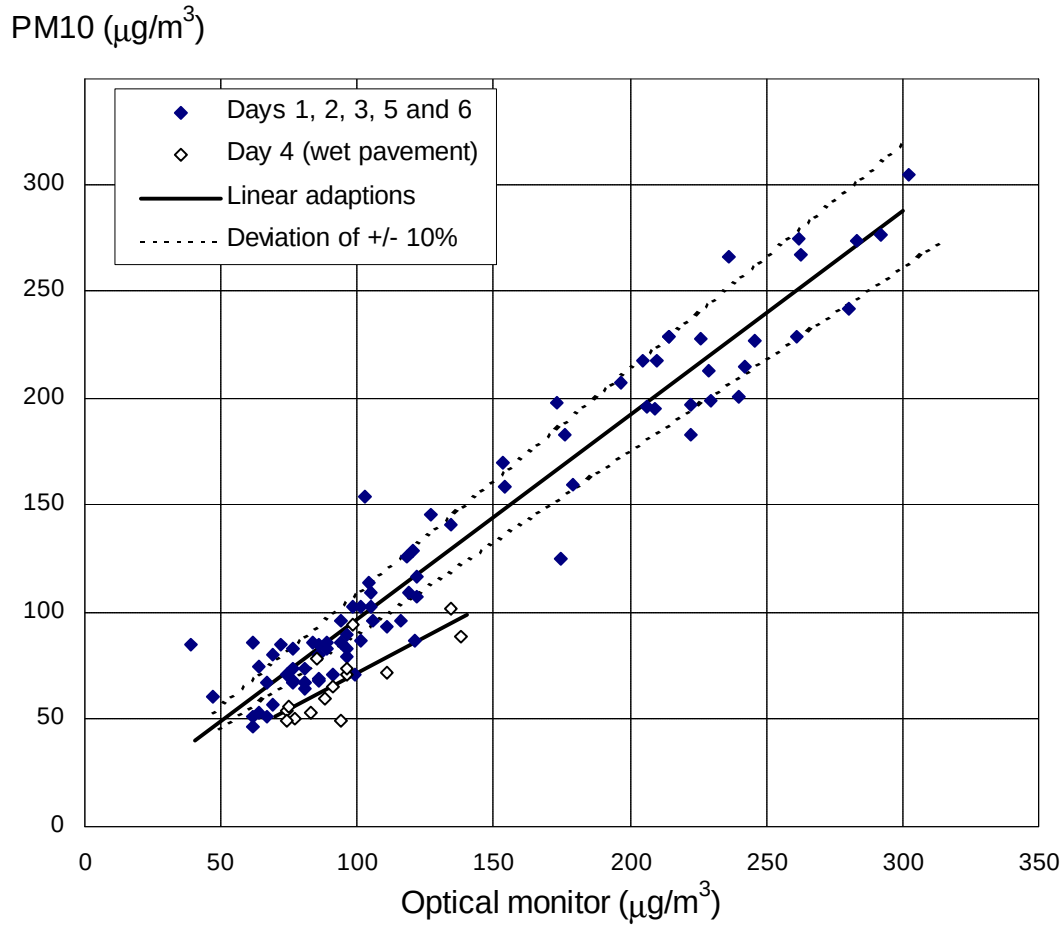


Figure 4: Scatter diagram of all parallel, PM10-related primary measurements. Data obtained on day 4 (wet pavement) are treated separately. Broken lines represent a deviation of the optical measurements of $\pm 10\%$.

All results of the intercomparison of the two monitors are summarized in table 2. Each of the listed concentration values is the mean of the series of primary measurements obtained with a given instrument on a given tunnel visit. Both PM10 and PM2.5 data are presented, and in the case of PM10, the percent difference between the two monitors is noted.

Measurements		Mean concentrations ($\mu\text{g}/\text{m}^3$)			
Day/Time of day	No.	SICK	PM10	Diff.	PM2.5
1/10:30-12:30	11	86	76	13%	70
1/16:00-18:00	13	69	70	-2%	
2/11:00-12:00	7	86	73	18%	
2/12:00-12:40	4	103			
2/14:00-16:00	11	94	94	0%	69
3/11:00-12:30	7	111	116	-4%	
3/14:30-16:40	6	138	130	6%	
3/15:00-17:00	4	123			
4/11:00-13:00	9	84	59	42%	49
4/14:30-16:40	6	111	81	37%	
4/15:00-17:00	4	103			
5/11:20-13:30	7	206	194	6%	
5/12:00-13:00	3	224			92
5/15:00-16:30	7	230	216	6%	
6/11:00-12:30	7	226	226	0%	
6/14:00-15:30	6	257	257	0%	
6/15:40-16:20	4	288			95

Table 2: A summary of all simultaneous light scatter (SICK) and gravimetric (PM10 and PM2.5) aerosol measurements of the six-day tunnel study. The values being compared are averages over each 1-2 hour measurement period. The percent difference of the optical result relative to PM10 is listed. The number of parallel primary measurements in each period is also noted.

Figure 5 shows examples of the daytime traffic pattern in the tunnel, which turned out to be quite repeatable. In the period 10:00-17:00 hrs, the small car traffic varied from less than 400 vehicles per hour to a rush hour peak of nearly 1400 veh./hr. In that same period, the large vehicle traffic remained fairly constant at about 90 veh./hr. This stability of the large vehicle traffic allowed plots to be made of hourly averages of the aerosol concentration as a function of the small car traffic rate. The results are shown in fig. 6 for both summer and winter conditions. As an aid to the following discussion, the two series of data points in this diagram have been approximated by straight lines. This is not to imply that the functional relationships involved are believed to be this simple.

Traffic (veh./hr)

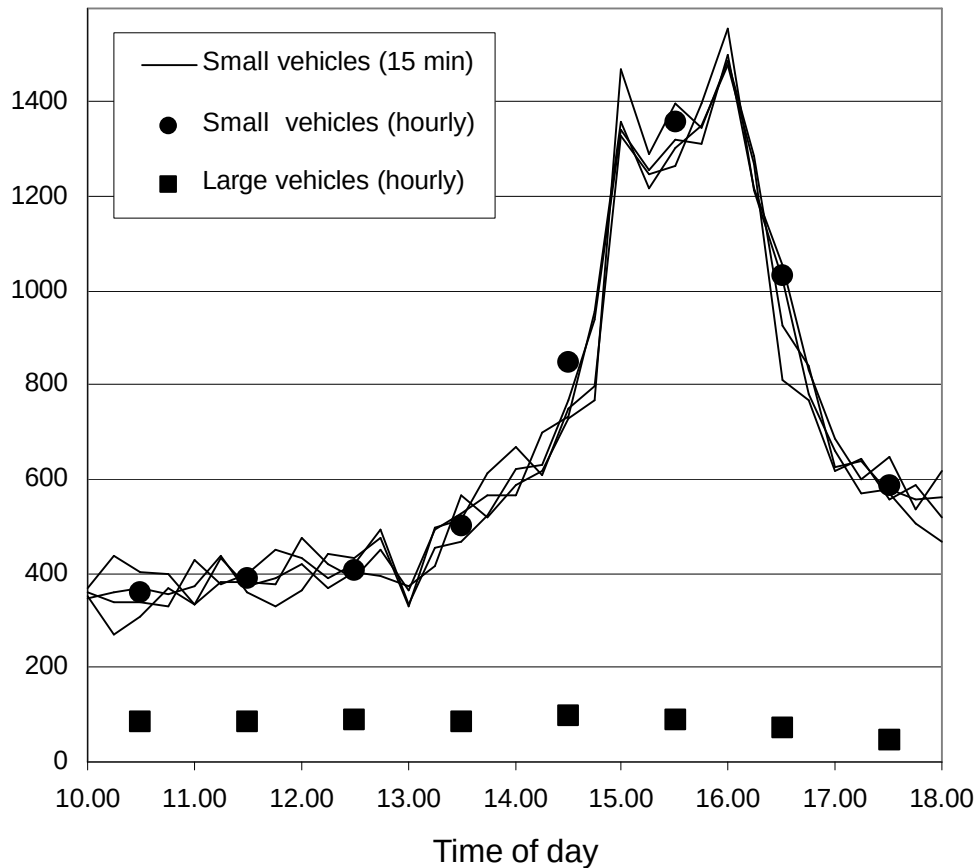


Figure 5: Typical daytime traffic in the Nygaard tunnel for vehicles shorter and longer than 5.5 m. Four days of quarter hour monitoring data for small cars demonstrate consistency in day-to-day traffic pattern. Hourly traffic rates for large vehicles in the period 10:00 - 17:00 hrs are moderate and nearly alike.

4. Discussion.

With the possible exception of the data from day 4, the scatter diagram of fig. 4 shows a surprisingly close overall correlation between the two instruments. Most matched values agree within $\pm 10\%$ for aerosol levels ranging from 50 to 300 $\mu\text{g}/\text{m}^3$. Some pairs of measurements differ considerably more, however, especially at the low end of the concentration range. One explanation may be that rapid changes in the tunnel aerosol concentration were perceived differently by the two instruments, an effect that is likely to have been most prominent on the first two days without instrument synchronization. Also, there were some indications that the optical monitor on rare occasions reacted to flashes or reflections of light associated with some large vehicles.

If average values over the entire 1-2 hour visiting periods are considered (table 2), the optical results agree quite well with the gravimetric measurements of PM₁₀. On the five days with dry road conditions, most of these averages were within $\pm 6\%$ of each other, i.e. well within the uncertainty associated with the gravimetric measurements. The two visits on which larger differences (13% and 18%) were noted, both occurred on the first two days.

On day 4 the optical monitor exhibited average values that were about 40% larger than those of the gravimetric monitor. This discrepancy may be a consequence of the humid conditions in the tunnel on that particular day. At the time, it was readily observed by the instrument operator that the rolling action of tires on the wet pavement led to the production of spray droplets, which in turn caused mists to develop behind passing vehicles. These mists were especially dense behind large vehicles. Such spray mists are likely to be sensed by the optical monitor, whereas they are unlikely to penetrate to the sampling region of the gravimetric monitor due to the sizes of the droplets.

Considering the purpose of the monitoring station, the deviating results on day 4 is hardly a cause for alarm. An overestimation of the PM₁₀ level on rainy days will be nullified by the fact that on such days, the aerosol concentration in the tunnel is likely to be significantly below levels set to trigger cleaning operations.

In the case of the fine particle fraction PM_{2.5}, the gravimetric measurements (table 2) indicate that the time-averaged concentration in the tunnel varies only moderately on a seasonal basis. Compared to averages of about 70 $\mu\text{g}/\text{m}^3$ under dry summer conditions, the result on a humid day in the fall was reduced 30%, whereas the observed averages on the two dry winter days represent an increase of 30-35%. These observations are consistent with the notion that particle emission in the form of vehicle exhaust is essentially independent of season, whereas the resulting ambient aerosol level may be influenced to some extent by environmental factors such as humidity.

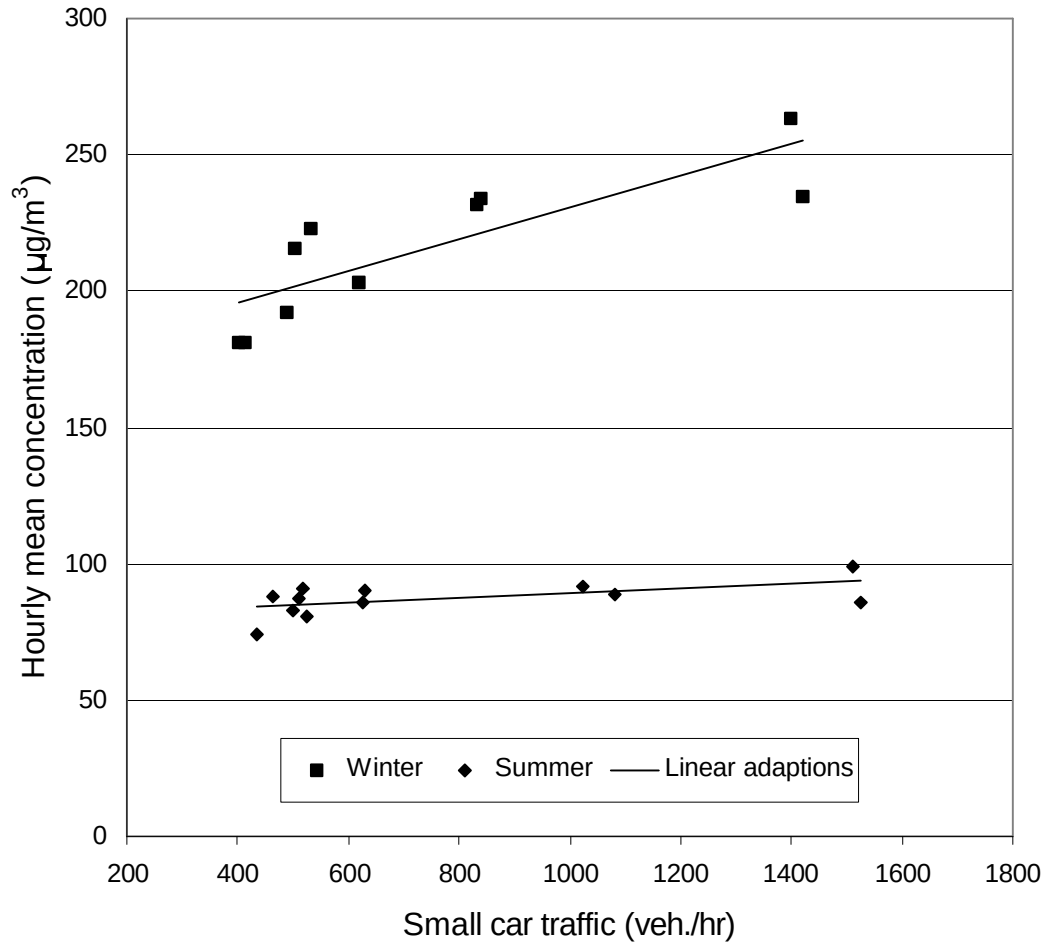


Figure 6: Hourly mean aerosol concentrations in the Nygaard tunnel as a function of the small car traffic rate. All computed means relate to periods of moderate and nearly constant large vehicle traffic. The two data sets reflect measurements made in summer (days 1 and 2) and winter (days 5 and 6), respectively, and have been approximated by straight lines for the purpose of clarity.

In the winter, substantial amounts of coarse particles are generated by the action of studded tires, resulting in a two-to-three fold increase in the PM₁₀ level. The fact that the PM_{2.5} level increases only moderately suggests that most of these coarse particles (75% - 90% by weight) are in the size range 2.5 - 10 µm. Aside from revealing the large summer/winter differences in the coarse particle burden, the PM_{2.5} measurements demonstrate that the optical monitor, at least in its present configuration, cannot be calibrated for the monitoring of PM_{2.5} on a year-round basis.

Figure 6 gives little or no indication of a correspondence between the tunnel aerosol concentrations and the small car traffic rate. Recalling that the large vehicle traffic was moderate and nearly constant throughout these measurements, one may have expected some sizable degree

of proportionality between these two factors. This lack of correspondence may be explained by assigning a comparatively high particle emission factor to the large vehicles. With some general assumptions made regarding the sources, sinks and behavior of the tunnel aerosol (the details are left out here), a rough estimate suggests that on the average, the summer emission from a small vehicle amounts to only about 1% of that of a large vehicle. A similar estimate for the coarse particles of the winter aerosol (excluding PM_{2.5}) yields a small-to-large vehicle emission ratio of about 5%. It is to be noted that these emission estimates relate to the emission of an "average" vehicle in each size group. It is quite possible that most of the pollution caused by the large vehicles, say, stems from a small percentage of units with excessive emissions.

The dominating role of large vehicles as a source of the summer aerosol inside the tunnel is undoubtedly a consequence of the well documented fact that diesel engines emit particles at much higher rates than modern gasoline engines. That the average large vehicle by far should outweigh the average small one as a source also of the coarse winter aerosol is harder to explain, since studded tires are carried by both small and large vehicles. Two factors may account for such a dominance, one being that heavy vehicles are more efficient at grinding dust from the pavement. More important may be that the occasional passage of a large vehicle through the tunnel causes a substantial reentrainment of previously settled dust within the tunnel enclosure.

From this tunnel study it may be inferred that large vehicles dominate as a source of both summer and winter traffic aerosols in the central Bergen region. This is consistent with the results of a field investigation made in 1996 in this same area⁽⁴⁾. In that study it was concluded that particle emissions from diesel powered vehicles constituted a major part of the aerosol burden along busy streets in downtown Bergen. Thus, both studies suggest that the most effective way of protecting the general public from excessive aerosol exposure in the central Bergen area would be to limit the pollution caused by large vehicles. This may be accomplished either by limiting the total traffic of such vehicles, or by taking measures to limit the emission from diesel powered engines, or both.

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