subscript n : normalized value
superscript - : average value of braking cycle
subscript i : initial value

Maximum temperatures of all recorded braking cycles were lower than 150°C. Therefore, we assumed that no thermal wear occurred, and the temperature did not affect the braking cycles or their wear rates. The sequence of braking cycles is also believed to be unimportant.

As seen in Eqs. (1) through (3), the important parameters governing NBC's are duration of braking cycle (Δt), initial speed (v_i), speed reduction (Δv), and average pressure ($\bar{p}$). When we analyzed the real braking cycles, we found that the braking cycle's duration is the most important factor determining the braking cycle patterns. Therefore, the representative normalized braking cycles (RNBC's) were classified using this parameter.

When the denominator in Eq. (2) is close to zero, background noises become too large after normalization. To eliminate the amplified mathematical errors caused by this condition, only those cycles that had speed reduction greater than 5 mph were used for speed normalization. For Eqs. (1) and (3), the lack of noise in time sampling or high average pressure made the normalization stable.

In this study, three RNBC's were found by averaging the NBC's of those typical subsets defined by durations of braking cycles: 0 - 15, 15 - 30, and 30 - 45 s. The RNBC's are plotted in Figures 1 through 3, and the corresponding normalized values, statistics, and other data are shown in Reference 6.

For braking cycles of short duration, (0 - 15 s) the speed reduction has the strongest correlation coefficient (-0.86) with the product of average pressure and cycle duration, which is approximately proportional to the momentum change of the car by brake friction forces. For braking cycles of long duration (15 - 30 and 30 - 45 s), the above statement is no longer true, and the speed reduction has the strongest correlation coefficients (-0.97 and -0.99, respectively) with initial speed (v_i). These statistics imply that most short brake applications were snubs (brake applications not leading to full stop). For long braking cycles, the brake was applied continuously after the car was almost stopped. This is further evidenced by Figures 1 through 3. In Figure 1, the speed continuously decreased to reach the final speed. But for long cycles (Figures 2 and 3), the speed reached the final value within 8 to 9 s. The normalized brake pressures were also relatively high during the first 8 s, then were reduced for long cycles. The later part of long braking cycles, with the normalized speed almost constant, is not believed to contribute an appreciable amount of wear debris due to small percent occurrences and lower speed in most cases. Considering this fact and the almost constant slope during the initial deceleration, the RNBC's can be approximated by truncating the later part with a constant speed and replacing the first part, corresponding to the initial 0 to 9 s, with a constant deceleration and pressure used by some previous investigators. Initial speed and average pressure do not differ as much with respect to cycle duration.

The frequency distribution of real braking cycles was found according to the subsets classified by initial speed, speed reduction, and cycle duration. The frequency distribution was used to generate RBC's and is summarized in Table 1 with other statistics. The subsets used in Table 1 could have been classified further by average pressure. But the average pressures had only slight variation for the braking cycles in a subset. This can be explained by the fact that when the driving road is flat, braking cycles have three degrees of freedom. Therefore, there was no need of further subdivision.

Table 1 shows that a majority of the cycles were less than 7.5 s in duration, amounting to approximately 64% of the cases, and 23% had brake applications from 7.5 to 15 s. The cycles with brake applications from 15 to 30 s or from 30 to 45 s comprised only a small portion, totaling 12% and 1%, respectively. Also most of the braking cycles had initial speed from 15 to 30 mph. About half of the brake applications were snubs. Overall, the brake applications were quite frequent, resulting in an average interval of 26 s.

GENERATION OF REPRESENTATIVE BRAKING CYCLES - Based on the frequency distribution and statistics shown in Table 1, real cycles representing an individual subset were generated by calculating real time, speed, and pressure from Eqs. (1) through (3).

Median values of intervals that specify subsets in Table 1 were employed for cycle duration, initial speed, and speed reduction. Using these values, we could calculate the RBC values from the normalized values shown in Figures 1 through 3.

When the brake and sampling system were installed, general tests were performed using the RBC for all collected cycles. Details of the tests are explained later. This representative cycle was generated similarly from the RNBC for all braking cycles. The calculated values of RBC's were converted to binary code by the computer and punched on paper tapes by ASCII for later use in simulation experiments.

TEST FACILITIES AND RUN OF REPRESENTATIVE BRAKING CYCLES

This section presents a description of the facilities for running RBC's, the measurements of their emission rates, and the estimation of emissions for inner-city driving.