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Development of an Exhaust System Complying with Tier 4 PM Regulations through Study of PM Formation Mechanisms in the Exhaust System

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The U.S. Tier 4 particulate matter (PM) requirement specifies a stringent mass limit of 0.5 mg/mi, with implementation anticipated in 2027. To address this target, vehicle-level evaluations were conducted using gasoline particulate filters (GPFs), which provide high nominal PM-filtration efficiency. Nevertheless, filter-paper (gravimetric) PM measurements exhibited substantial variability and, in some cases, exceeded the Tier 4 limit. We hypothesize that this behavior arises from interactions between water-soluble exhaust species (e.g., NH_3 and water-soluble inorganic species, WSIs) and condensate within the exhaust system; as exhaust temperature increases, condensate evaporation can release these dissolved species in particulate form into the exhaust stream. The objective of this study is to identify the fundamental mechanisms responsible for excessive PM emissions and large test-to-test variability and to propose effective PM-reduction strategies. Additionally, by quantifying PM-forming species remaining along the flow path from the vehicle exhaust to the PM-measurement instruments, this work aims to establish a method for accurately determining the portion of PM emissions attributable solely to the vehicle. Based on PM-emission evaluations across multiple vehicles, the following conclusions were drawn. As illustrated in Fig. 1, PM emissions were classified as originating from three segments of the system: ① the catalyst assembly, ② the post-catalyst exhaust hardware (muffler to tailpipe), and ③ the PM sampling lines and PM instrumentation. Consistent with prior development results, compliance with the Tier 4 PM standard could not be achieved by relying on the GPF alone. To mitigate PM generated in segment ②, we evaluated the PM-reduction effectiveness of an NH_3 -reduction catalyst. In addition, to quantify PM arising from contamination in segment ③, we measured background PM—defined as PM captured when a constant flow of dilution air is supplied without vehicle operation (i.e., dilution air only).

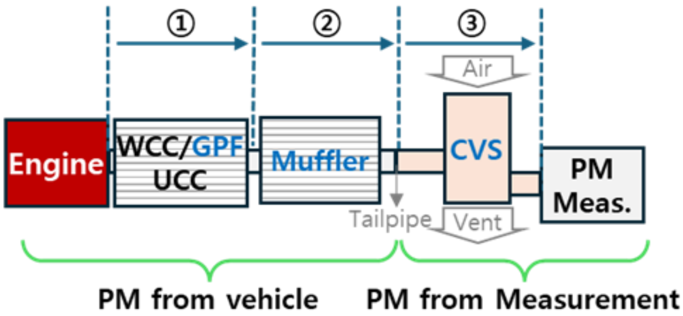

Fig. 1 PM measurement layout and classification of PM sources

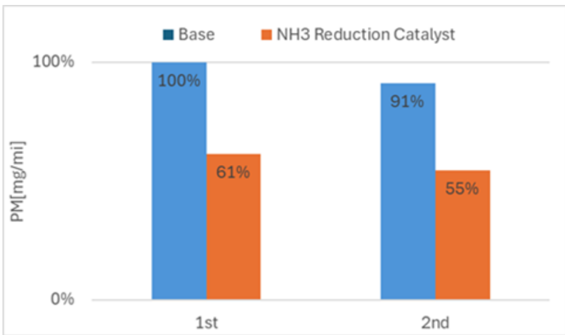

Fig. 2 PM reduction by NH_3-reduction catalyst

The key findings from this sequence of evaluations are summarized below.

1) it is necessary to consider and minimize PM emissions from all segments of the system, namely the catalyst assembly, the post-catalyst exhaust hardware, and the PM sampling lines/instrumentation.
2) To minimize PM generated/released in segment ② of Fig. 1 (post-catalyst exhaust hardware, i.e., muffler to tailpipe), applying an NH_3-reduction catalyst is effective; the evaluations showed approximately 40% PM reduction as shown in Fig. 2.
3) To reduce PM attributed to segment ③ of Fig. 1 (PM sampling lines/instrumentation), background PM should be measured and subtracted—i.e., apply "vehicle PM − background PM"—which facilitates meeting the Tier 4 PM limit.
4) Under high temperature and high flow conditions, PM-forming species previously deposited in segments ② and ③ are readily desorbed/purged and subsequently collected by the filter-paper method. Consequently, US06 generally shows higher PM emissions and larger test to test variability than FTP-75.