VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

The automotive industry is looking to address environmental issues not only by raising the thermal efficiency of the internal combustion engines that make up the conventional powertrain, but also by developing vehicles that use a power source other than an internal combustion engine, such as BEVs, FCEVs, or hydrogen engine-powered vehicles, to achieve zero CO_2 emissions while driving. In that context, many automakers are betting on BEVs to achieve the zero CO_2 emissions in 2035 target set by many countries. This has increased both the number of BEV models available and sales of such vehicles.

In BEV development, reducing weight is required to boost the all-electric range (AER), and automakers are also working to develop a dedicated platform providing an optimal solution that also encompasses NVH. The absence of engine noise means the cabin becomes quieter, making technology that significantly reduces road-, wind-, and motor noises necessary. Moreover, new advances are anticipated in integrated sound design technologies that takes human acoustic psychology into account to provide feedback to the driver on vehicle acceleration and deceleration when driving in electric mode with no engine sound.

At present, improving the fuel efficiency of internal combustion engines and HEVs is still considered a crucial means of reducing CO_2 emissions. Consequently, research not only on NV technology to compensate for the increase in vibratory force that follows from higher fuel efficiency, but also on technology to fine tune engine operation—including charging and discharging efficiency in HEVs—to achieve good balance with comfort. Technology offering even better balance is expected to be required in the future.

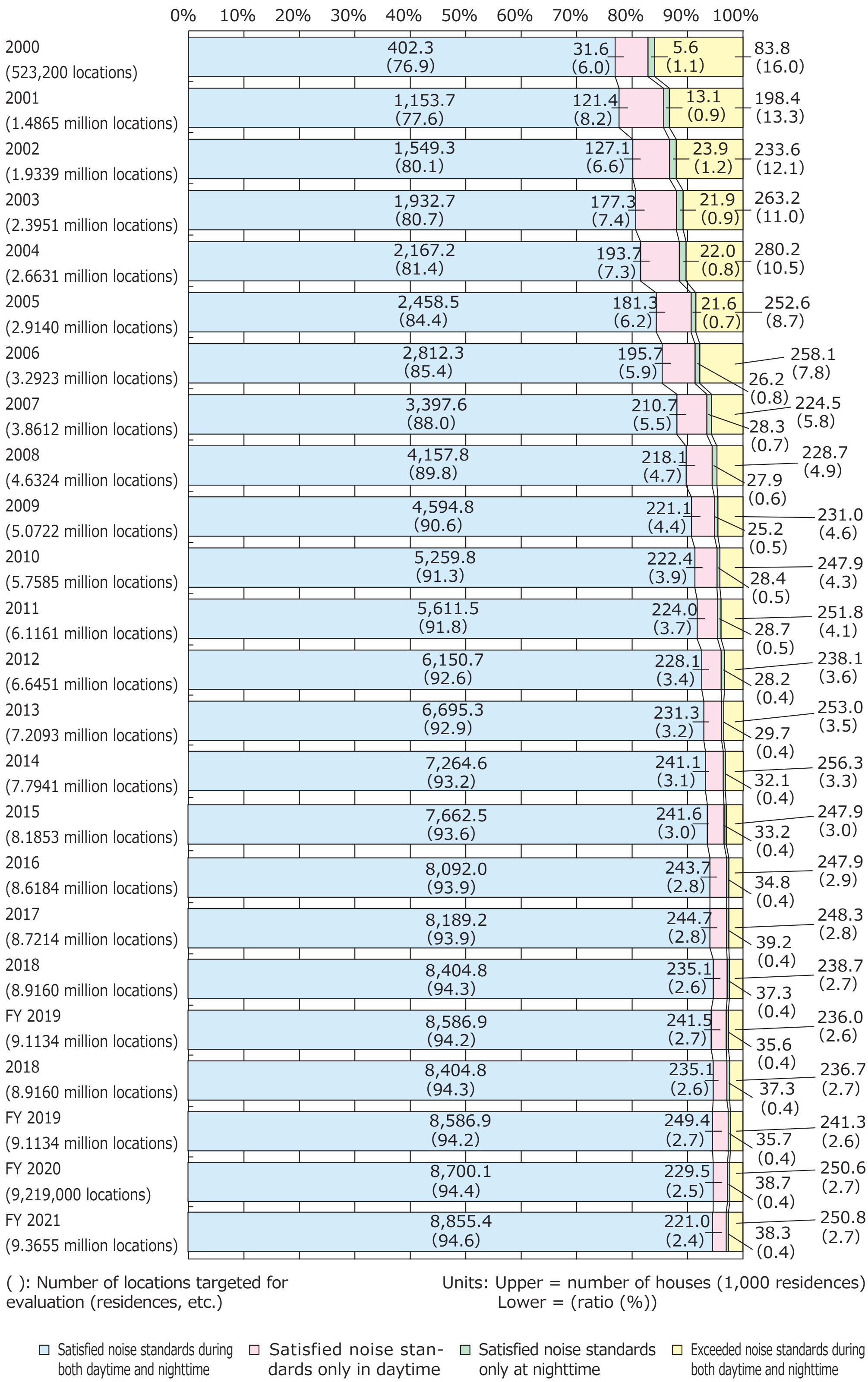
Developing new platforms and making major improvements in performance, independently of the power source, calls not only for advances in MBD and CAE technologies, but also for progress in technologies that achieve a greater balance of performance than ever.

2 Road Traffic Noise

Since their introduction in 1951, vehicle noise regulations in Japan have been gradually strengthened, and environmental noise has steadily decreased. The new international noise standard (UN R51-03) was introduced in 2016. This regulation presents noise reduction requirements that are more in tune with actual urban driving conditions. According to the report on the continuous monitoring of vehicle noise conducted by the Ministry of Environment since 2000, the attainment of environmental standards has been improving moderately over time, as shown in Fig. 1. However, there are still regions where the standards are not met, and continuous improvement in environmental noise remains necessary.

Reducing environmental noise will require comprehensive discussion that encompasses standalone automobile noise reduction measures as well as traffic flow measures, road structure measures, and measures adapted to conditions in individual regions. Reports that compare the ASJ RTN Model road traffic noise evaluation method widely used in Japan with the methods used in European countries, as well as reports on the noise map-based prediction and evaluation of noise applied in Europe and on the building of structural models to evaluate discontent about the environment around arterial roads using image grids created from surveys of residents have create expectations that those technical tools and analysis results will lead to taking effective measures that improve the noise environment.

To address standalone automobile noise, harmonization with the Phase 3 UN R51-03 next-stage regulations has been examined. Japan has decided to apply the regulations as of October 2024 (2026 for existing vehicles). Studies of actual vehicle noise data on how effective implementing Phase 3 is at reducing environmental noise have



Source: Ministry of the Environment website

Fig. 1 Status of Compliance with Environmental Noise Standard in Japan (nationwide change over time) predicted an effectiveness of 0.6 dB (A). However, that figure has been reported to drop to 0.3 dB (A) when switching to commercial tires widely available on the market. This indicates just how much tire road surface noise contributes to road traffic noise.

The mechanism that produces tire road surface noise originates in a variety of mechanical phenomena that occur between the tire and the road surface and whose details are still not fully understood. Consequently, considerable research on that subject is being carried out. One investigation focused on the deformation behavior of the tire tread blocks and measured their standalone strain and acceleration, as well as the sound pressure in the sub-grooves between the tread blocks, and compared them to the frequency characteristics of tire road surface noise. The results of that investigation have raised expectations for further elucidation of the noise generation mechanism and reduction in tire road surface noise.

In contrast, users making vehicle customizations that generate a lot of noise, such as replacing the muffler, are the source of many complaints about noise near roads. Various countries are looking into technology to identify such vehicles. In Japan, this is policed through the proximity exhaust noise test, but that test itself is cumbersome. In one report of a simple and effective approach, the use of AI, a technology used in various fields, has been demonstrated to enable the identification of vehicles equipped with a muffler that exceeds the regulatory values based on the noise emitted while driving. A revision of the verification system for the performance of the muffler and other components, as well as standalone tire noise regulations, are under consideration as part of measures to reduce noise for vehicles in use. Progress is being made on efforts to establish comprehensive measures to reduce road traffic noise and, by extension, environmental noise.

3 Powertrains

3. 1. Internal Combustion Engines

The Euro 7 draft announced in Europe in November 2022 is one of the several gradual tightening of emissions regulations leading to accelerated automobile electrification. However, it will take time for BEVs to become widespread, and more improvements in the thermal efficiency of internal combustion engines are also required. That transition period will call for technology that effectively reduces the vibration and noise increase resulting from enhanced thermal efficiency.

Technologies to speed up combustion are being developed to raise thermal efficiency. However, several analyses of the relationship between the resulting increased noise and both in-cylinder pressure and the heat release rate. One report analyzed the resonance mode of the sub-chamber in the context of analyzing combustion noise generation factors in the unique 6 to 9 kHz band of gasoline engines featuring a jet combustion sub-chamber to enhance thermal efficiency. Another report analyzed the relationship between heat release rise characteristics and the frequency characteristics of the internal pressure in the 1 to 2 kHz band.

Several papers on research to reduce the vibrations cause by combustion have also been published. In one reported instance, focusing on the thin part of the connecting rod made it possible to decrease vibrations by preventing the coupled frequency of the piston and connecting rod from matching the specific vibration frequencies of other engine structures. A different paper focused on the main bearing and reduced engine vibrations by applying a taper angle matching the elastic deformation of the crankshaft to decrease the roughness contact pressure of the bearing.

Other research sought to reduce the mechanical noise covered by the combustion noise, and applied a running transfer path analysis (TPA) to carry out a contribution separation on the mechanical noise and improve the specific accuracy of the target locations. In HEVs, the role of the internal combustion engine is not limited to simply trying to generate electricity more efficiently. It also requires a performance design that does not adversely affect the quietness provided by motor drive at low speeds. There has also been a report of successfully balancing noise reduction and fuel efficiency by optimizing control of the engine operating range and number of operations using a variable compression mechanism, and increasing or decreasing engine rotation while driving according to the vehicle speed.

As described above, research on technology to improve internal combustion engine efficiency and reduce noise is expected to continue during the ongoing period of transition to electrification.

3. 2. Electric Motor Systems

In BEVs, which are rapidly replacing internal combustion engine vehicles, the high frequency noises from components such as motors and inverters present an even greater issue than in hybrid vehicles.

There are initiatives to quantify the discomfort produced by high frequency noises in BEVs underway to address this issue. In one example, pure tones representing motor and other noises, and broadband noises representing background noise inside the vehicle were used to ascertain the threshold for noise projection and the extent to which it was a bother.

There is also active development on technologies to reduce motor noise. In one development example, the electromagnetic excitation force in the low torque range was reduced by controlling the current in both the starter and the rotors of synchronous motors that use an external field rather than relying on neodymium magnets in the rotors.

Efforts to realize a circular economy are anticipated to result in developing motors that use substitute low environmental impact materials or recycled materials. That, in turn, is expected to increase the need for noise reduction technologies adapted to those materials.

3. 3. Drive Power Transmission Systems

In the wake of stricter environmental performance requirements, there have been many reports concerning research on NV phenomena in torsional systems, such as the rattling noise of gears excited by the increased torque fluctuations resulting from the improved efficiency of the drive power source.

The analysis of nonlinear vibration phenomena originating in torsional damper characteristics and rotation speed, transfer torque, or other operating conditions using a method called return map is shedding light on physical behaviors. Universities are actively researching new mechanisms for the development of devices related to torsional system NV phenomena, such as a continuous variable stiffness dynamic damper with a simplified structure achieved through a rolling mechanism, or a two-way roller clutch that realizes a tightening structure without the backlash that causes gear rattling noise.

One example of improving development processes for powertrain products is the use of a simulator with an engine model attached to the drive dynamometer (Fig. 2) to enable bench performance evaluations of drive power transmission in the initial stages of development.

Papers covering a broad range of topics from device development to system development have been published, raising expectations for further improvements in noise reduction or development process efficiency.

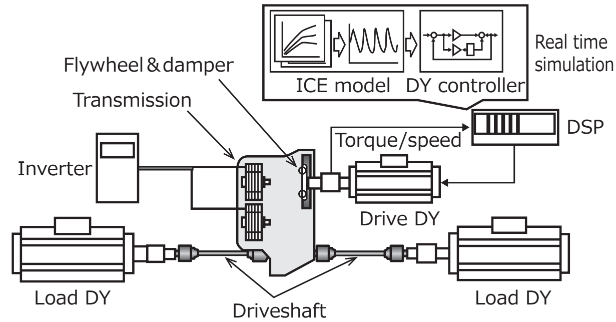


Fig. 2 Simulator with an Engine Model Attached to the Drive Dynamometer

4 Tires, Suspension Systems, and Vehicle Bodies

4. 1. Tires and Suspension Systems

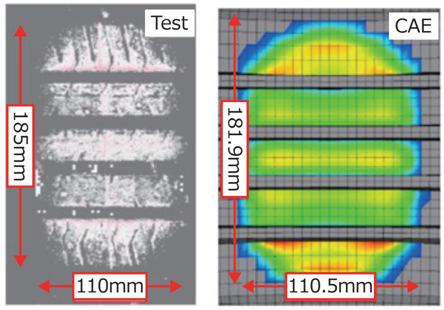
The stepping up of the transition to BEVs and of initiatives to achieve automated driving has increased the importance of part designs that account for noise and vibration for the purpose of further enhancing comfort and quietness.

For tires, improving the accuracy of calculation models is required to validate road noise performance. One research project on that topic created a calculation model capable of assessments reaching 400 Hz by adding static characteristics such as the static load radius and the contact surface area (Fig. 3) to an objective function, identifying the Young's modulus of the material, and significantly raising prediction accuracy for vibration response and interior noise.

For suspensions, efforts are directed at building a standalone suspension measurement system to measure hysteresis characteristics with a high degree of accuracy, and to elucidate the contribution of individual components (Fig. 4), for the purpose of enhancing ride comfort performance. There have been examples of modifying part characteristics based on that analysis, and of applying technology that controls hysteresis characteristics to mass production vehicles.

Low suspension rigidity is effective at reducing inputs from the tires when driving over bumps in the road, but leads to the problem of vibration in the suspension itself. One proposed solution involves taking the link between suspension members and the differential gear mounting system into account, and assessing ways to improve vibration convergence in the longitudinal direction of the vehicle body.

There are expectations for initiatives to further im-



Axle Load	
Test	4,300 N
CAE	4,464 N
Error	3.80%

Fig. 3 Accuracy of Static Characteristics of Tire

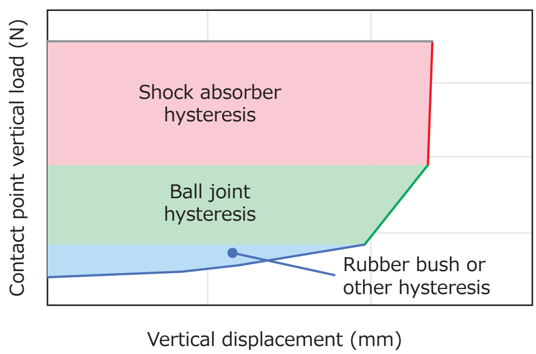


Fig. 4 Schematic Diagram of Contribution of Components

prove the accuracy of simulations for tires and suspensions, as well as for advances in technologies that achieve compatibility with systems that cross over into fields other than tires and suspensions.

4. 2. Vehicle Body and Interior Materials

The need to improve the fuel efficiency of ICE vehicles and to reduce vehicle body weight in response to demand for longer BEV cruising ranges has become greater than ever amid growing environmental awareness. At the same time, calls to improve noise and vibration performance to create a comfortable vehicle interior space are intensifying. The desired performance must be achieved within the constraints imposed by limited space, mass, and cost.

Finite element models are becoming ever more detailed in an attempt to apprehend the mechanisms involved. However, the number of eigenmodes keeps rising, and understanding those mechanisms takes time. Research addressing this issue includes an example seeking to make instant structural changes that reduce road noise by grouping eigenmodes using principal component analysis and singular value decomposition, as well as a reported method to classify the global mode based on the contribution of the subsystem modes, and quantitatively evaluate their relevance.

Vehicle development is also now increasingly seeking to raise development efficiency by expanding the number of common parts, and the number of newly developed parts is limited. Research involving simultaneously controlling multiple resonances based on the transfer function synthesis method has been introduced as a design method aimed at efficiently improving performance by modifying the structure of only those parts. The use of low environmental burden or recycled materials is increasingly being considered to achieve carbon neutrality. Examples include reducing vehicle interior noise originating from the tires during low speed driving, which is more noticeable in BEVs, using a Helmholtz resonator made of pulp mold, as well as assessing a modeling method to estimate the acoustic properties of heterogeneous materials made from rebonded foam. Many aspects of weight reduction and noise and vibration performance are in conflict, and elucidating the mechanisms behind complex noise and vibration phenomena is essential to balancing those conflicting aspects. Advances in analysis technologies providing deeper understanding in a shorter time, as well as in innovative reduction technologies that are not bound to existing vehicle body structures or materials, are anticipated.

4. 3. Trim and Aerodynamics

The tire, aerodynamic, and electrical component noises brought to the forefront by electrification must be addressed. Examples of approaches taken in BEVs introduced into the market include expanding the surface area of conventional sound insulating and sound absorbing materials, and optimizing layouts by making the hole surface area of parts smaller. One reported initiative to mitigate noise infiltration by reducing gaps in the vehicle body and improve the sound insulation of the vehicle body while reducing the amount of sound absorbing material used consolidates methods to predict the equivalent aperture area, an evaluation index of vehicle body gaps, from the results of path analysis performed with a CAD model.

As part of efforts to further improve sound insulation performance, methods of installing fiber soundproofing materials within weight and volume limits, as well as structural design technology for members, have been established. The finite element method was used to report the effect of the compression width and compression ratio on sound insulation performance by focusing on processing techniques for openings where sound insulating material made of high density felt and air-impermeable film does not cover the vehicle panels. Another paper describes a high redundancy design technique intended to reduce road noise. Rather than relying on the sound absorbing properties of the material itself, that technique uses a fine perforated panel and resonance box to factor in manufacturing variations in hole size for members that absorb a specific frequency.

At the same time, there is constantly growing demand to address the wind noise made more noticeable by improvements to vehicle quietness, and research on two phenomena has been published. The first phenomenon is the underfloor low frequency wind noise. The source of the noise itself is unknown, leading to reports on attempts to use detailed underfloor measurements to clarify the mechanism and establish predictive technology. A separate report describes an attempt to elucidate the mechanism using a simple model. The second phenomenon is fluctuations in wind noise. They originate from the time variation due to factors such as natural wind conditions affecting airflow around a vehicle in motion. There have been examples of research on methods to reproduce those variations and on evaluation methods matched to human perception.

Expectations are now placed on technological advances from a variety of angles ,such as noise source measures against a broad range of input sources, path blocking, and sound insulation performance improvements, which are not limited to the two areas of quietness and weight reduction, but also take the environment into account.

5 Development Technologies (MBD/MDO/AI)

Conventional noise, vibration, and ride comfort development technologies have centered around increasing the accuracy of 3D CAE models and creating analysis techniques to identify specific contributing locations for the purpose of understanding even more detailed mechanisms. In contrast, newer vehicle development processes are expected to be shorter to address customer needs in a timely manner. This is making it necessary to validate vehicle performance in the initial stages of development and determine specifications and structures. Consequently, multidisciplinary design and optimization (MDO), promising AI technologies that can make highly accurate performance predictions even without detailed shape data, and model-based development (MBD), which front loads development are drawing attention as new development technologies. There are more and more examples involving the assessment of those technologies.

One reported example of MDO builds large scale nonlinear topology optimization technology that accounts for the nonlinear problem of energy absorption in a collision to simultaneously optimize the linear problems of rigidity and NVH. A different paper describes using CAE and AI technologies to quantify the trade-offs between vehicle performance and mass when the vehicle body frame layout and styling is changed at the vehicle development planning stage. One example that used AI in the design of noise and vibration performance reported that building a one-dimensional model that predicts transmission force from intermediate characteristics, such as the suspension eigenvalue and mass information, made it possible to create a technique to allocate target values to the intermediate characteristics, as well as to build an AI model capable of predicting tailgate eigenvalues from a picture of the tailgate. One report describes studying the feasibility of rear mounting system multi-performance through MBD that uses a response surface. In that example, the application of MBD that uses a response surface involves assessing how to make the multi-performance range clear through approaches such as assessing multi-performance synchronization, applying a domain mapping matrix (DMM) to define a clear design procedure, and the set-based method.

Feasibility studies of vehicle performance at the initial development stage require a one-dimensional model capable of prediction performance, as well as MBD that can make use of that model, but the complexity of noise and vibration mechanisms had impeded the building of one-dimensional models and, consequently, limited the application of MBD. However, recent advances in AI technology hint at the possibility of building a one-dimensional noise and vibration model. Building and fusing those technologies is expected to front load development in the fields of noise and vibration and of ride comfort.

6 Sound Quality Evaluation

The growing spread of BEVs has led to a greater proportion of vehicles sold with powertrains that replace engines with motors. One benefit for users is the improved quietness in the cabin due to the absence of engine noise.

In contrast, relatively small noises have become more perceptible. Gear, motor, inverter, and other powertrain system noises are now prone to being factors in driver discomfort. Research on noise quality evaluations based on EV noise perception, as well as on pure tone recognition evaluations using broadband noise masking, is being conducted to address that issue.

Another issue stemming from the transition to BEVs is the decrease in noise-based vehicle feedback to the driver. Extensive research on generating driving sounds to address that issue has already been conducted in the past. However, the tones of such generated sounds may not match user preferences. Therefore, research that apprehends the driving environment and interprets the driver's feelings using AI to generate appropriate in-cabin sounds is being carried out. This is expected to eventually lead to offering sounds that automatically change tones based on user preferences and driving conditions.

At the same time, in-cabin noises other than the powertrain noises produced while driving, road noise, and sounds, are anticipated to become important. One example, the sound quality evaluation of switch operation noises, has been the subject of research to evaluate the impression produced by onomatopoeia-based expressions.

Further enhancing the comfort of the vehicle interior is expected to result in more cases of research in areas such as the conceptual integration of driving sounds and switch operation tones, or sound design for the whole vehicle during automated driving.

7 Ride Comfort

Answering growing expectations for more comfortable movement spaces, as well as calls for enhanced ride comfort, requires technologies that improve performance at a lower cost. The reduction in body weight stemming from fuel economy and AER requirements has created the issue of achieving balance with both handling performance and noise and vibration performance.

Accordingly, initiatives adopting a fresh perspective have been presented. In the field of active suspension control, they include research on a method to perform preview control by estimating unsprung mass from a database, as well as an attempt to reduce the cost of a semi-active suspension system by replacing sensor functionality with machine learning.

In contrast, ride comfort performance involves human elements in addition to mechanical properties, making it difficult to predict performance in the initial stages of development. Consequently, research on ride comfort performance evaluations that encompass human elements, and on finding quantitative indices of occupant perceptions of comfort, is being carried out. Reported examples include assessing a ride comfort performance prediction method using biosignal data and an emotion structure model, as well as research on applying hierarchical clustering on vehicle vibration data to extract feature waveforms with the potential to affect subjective evaluations of ride comfort.

There is also ongoing research on basic technologies. Papers describing an analysis of tire effect on ride comfort performance that takes dependence on speed into account, and the development of an engine mount that applies material offering both high damping characteristics for ride comfort performance, and low dynamic spring characteristics for noise and vibration performance, have been published.

Ride comfort will remain an unchanging value in mobility, setting expectations for continued improvements in performance.

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