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Vehicle-Based Evaluation of 12-V SLI Battery Cranking Performance under Ambient Cold-Start and Hot-Start Conditions

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ABSTRACT

Reliable engine starting in conventional vehicles depends on the SLI battery's ability to deliver high cranking current while maintaining voltage under load. This study evaluated a 12-V maintenance-free lead-acid SLI battery rated at 450 A CCA under practical ambient cold-start (20–30 °C) and hot-start (85–105 °C) conditions. Testing was conducted over four consecutive days using measured CCA, CCA ratio, minimum cranking voltage, open-circuit voltage (OCV), and starter duration. The tested battery showed generally better cranking indicators under the hot-start condition, with higher measured CCA, higher CCA ratio, slightly higher minimum cranking voltage, and shorter average starter duration. OCV remained stable at approximately 12.5–12.6 V, indicating that the observed cranking differences were not mainly associated with major no-load voltage variation. The combined use of CCA, cranking voltage, OCV, and starter duration provides a practical diagnostic basis for evaluating SLI battery starting readiness.

Keywords
SLI battery; cold cranking amps; cranking voltage; open-circuit voltage; automotive battery diagnosis

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INTRODUCTION

Lead-acid batteries remain widely used in automotive starting-lighting-ignition (SLI) systems because they are relatively affordable, robust, and capable of delivering high pulse current during engine cranking. Their role remains important in conventional vehicles, where the starter motor requires a short but high-current discharge to initiate engine combustion. Recent studies have shown that lead-acid and lead-carbon battery systems continue to be relevant for applications requiring stable discharge performance, although their response is strongly influenced by temperature and operating condition [1]–[3].

Cold Cranking Amps (CCA) is one of the most practical indicators used to describe the current-delivery capability of an automotive battery during starting. In standardized battery terminology, CCA refers to the ability of a battery to deliver current under low-temperature conditions while maintaining a specified minimum voltage. However, in practical vehicle operation, starting performance is not determined by CCA alone. Minimum cranking voltage is also important because the starter motor produces a high transient load that can cause voltage sag during cranking [4], [5].

Open-circuit voltage (OCV) is commonly used as a supporting diagnostic variable because it reflects the no-load voltage condition and is often associated with state of charge and battery health estimation [6], [7]. In conventional vehicle applications, battery management and diagnosis therefore require a combined interpretation of current delivery, voltage response, and practical starting behavior rather than relying on a single parameter [8]. Furthermore, temperature is a major factor affecting SLI battery response. At lower temperatures, increased electrolyte viscosity and slower ion transport can increase internal resistance and reduce available discharge current. In contrast, warmer conditions can improve short-term electrochemical activity and charge transfer, although prolonged thermal exposure may accelerate degradation processes [2], [9], [10]. Previous research has also examined lead-acid battery health estimation using electrochemical impedance, charging-curve behavior, degradation modeling, and valve-regulated lead-acid battery analysis [11], [12]. These studies provide important electrochemical and diagnostic foundations, but many of them were conducted under controlled laboratory conditions or focused on model-based evaluation rather than practical starting behavior in a vehicle.

Other recent studies have improved the understanding of lead-acid battery performance through electrolyte modification, grid corrosion control, electrode imaging, and additive development. For example, electrolyte and electrode modification have been reported to influence cycle life, corrosion resistance, active-material behavior, and discharge stability in lead-acid or lead-carbon battery systems [13]–[19]. These material-level investigations are valuable for explaining the internal mechanisms that affect battery performance. However, they do not fully represent the practical diagnostic situation faced in automotive maintenance, where technicians often rely on accessible parameters such as CCA, minimum cranking voltage, OCV, and starter duration.

Based on this literature, a specific gap remains in the practical vehicle-based evaluation of a 12-V SLI battery using combined cranking indicators under ambient cold-start and hot-start conditions. Previous studies have extensively discussed temperature effects, electrochemical behavior, OCV-based diagnosis, and health-estimation methods [5], [6], [20], but fewer studies have interpreted measured CCA, CCA ratio, minimum cranking voltage, OCV, and starter duration together during actual vehicle starting. Therefore, this study evaluates a 12-V maintenance-free lead-acid SLI battery with a rated CCA of 450 A under two practical operating conditions. The objective is to analyze how the combined diagnostic parameters describe the starting capability of the tested battery and to provide a practical interpretation that can support automotive battery diagnosis and preventive maintenance decisions.

METHOD

The test object in this study was a 12-V automotive lead-acid starting-lighting-ignition (SLI) battery with a manufacturer-rated Cold Cranking Amps (CCA) value of 450 A. The battery was evaluated over four consecutive days, from 24 January to 27 January, under two practical vehicle operating conditions: ambient cold-start and hot-start conditions. The ambient cold-start condition refers to the starting condition before engine warm-up at 20–30 °C, whereas the hot-start condition refers to the starting condition after engine operation at 85–105 °C. The purpose of this procedure was to compare the cranking response of the same battery under two different operating thermal conditions using the same vehicle-based measurement procedure. Although this study was not designed as a standardized laboratory CCA compliance test, the selection of rated CCA, cranking voltage, and starter-battery diagnostic parameters is consistent with starter-battery testing frameworks and recent measurement approaches for lead-acid starter batteries [21]–[25].

This study used one unit of a 12-V lead-acid SLI battery as the test sample. Therefore, the results should be interpreted as an empirical evaluation of the tested battery under the specified operating conditions rather than as a general representation of all SLI batteries. To maintain procedural consistency, the same battery was repeatedly tested over four consecutive days under both ambient cold-start and hot-start conditions. Although the use of a single battery limits the generalizability of the findings, the repeated observations provide practical information on how CCA, minimum cranking voltage, open-circuit voltage (OCV), and starter duration behave under different vehicle starting conditions.

The measured parameters consisted of measured CCA, CCA ratio, minimum cranking voltage, OCV, and starter duration. OCV was measured under no-load conditions before engine starting and was used as a supporting indicator of the battery's no-load voltage condition, which is commonly associated with state-of-charge and health-related battery interpretation [6], [7]. During engine cranking, the minimum terminal voltage was recorded to identify the deepest voltage sag caused by the starter load. This load-response behavior is relevant to battery discharge assessment and starter-battery diagnostic evaluation [4], [5], [25]. Starter duration was also recorded to determine the time required for successful engine starting, which provides a practical indicator of cranking adequacy in vehicle operation.

The relationship between measured and rated current capability was expressed using the CCA ratio, as shown in Equation (1).

$$\text{CCA Ratio} = \frac{\text{Measured CCA}}{\text{Rated CCA}} \times 100\% \quad (1)$$

where measured CCA is the current capability obtained from the battery analyzer, and rated CCA is the nominal value specified by the battery manufacturer, namely 450 A. The CCA ratio was used to compare the measured cranking-current capability with the manufacturer-rated specification.

All measurements were repeated systematically for each observation day under both operating conditions. Accordingly, the resulting dataset consisted of daily recorded values of measured CCA, CCA ratio, minimum cranking voltage, OCV, and starter duration for both ambient cold-start and hot-start conditions.

The experimental procedure is summarized in Figure 1. The schematic shows the main test components, namely the vehicle, starter motor, SLI battery, battery tester, and multimeter, as well as the measurement sequence under ambient cold-start and hot-start conditions. The research design is summarized in Table 1, while the operational temperature conditions are described in Table 2. The technical specifications of the test vehicle and battery are presented in Table 3 and Table 4, respectively.

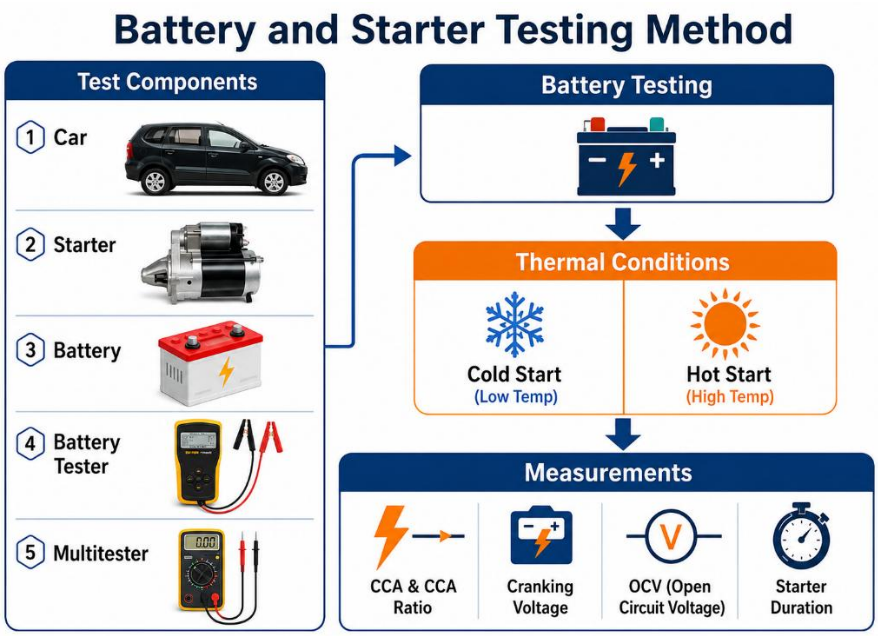

Figure 1. Schematic of the battery and starter testing method under ambient cold-start and hot-start conditions.

Table 1. Research Design

Group	Treatment	Experimental Output	Condition
R1	Ambient cold-start testing	CCA, CCA ratio, minimum cranking voltage, OCV, and starter duration	Ambient cold-start
R2	Hot-start testing	CCA, CCA ratio, minimum cranking voltage, OCV, and starter duration	Hot-start

Table 2. Description of Operating Conditions

Condition	Temperature Range	Engine State	Description
Ambient cold-start	20–30 °C	Before engine warm-up	The vehicle was started when the engine and surrounding starting system were close to ambient temperature. This condition does not represent standardized laboratory CCA testing at sub-zero temperature, but practical cold-start operation in the vehicle environment.
Hot-start	85–105 °C	After engine operation	The vehicle was started after engine operation, when the engine bay and starting system were exposed to a higher operating temperature.

Table 3. Specifications of the Test Vehicle

Item	Specification
Type	1.3L K3-VE
Engine	4-cylinder, 16-valve, DOHC, VVT-i
Bore × stroke	72.0 mm × 79.7 mm
Maximum torque	120 Nm at 4,400 rpm
Maximum power	92 PS at 6,000 rpm
Fuel type	Gasoline
Fuel system	Electronic Fuel Injection (EFI)

Table 4. Specifications of the Tested Battery

Item	Specification
Type	Maintenance-free / sealed lead-acid battery
Code	NS60 (46B24R)
Capacity	45 Ah
Voltage	12 V
Dimensions	238 mm × 129 mm × 203 mm

RESULTS AND DISCUSSION

Results

This section presents the experimental results of 12-V SLI battery performance testing under ambient cold-start and hot-start conditions. The results are presented through three graphical outputs: cold-start performance in Figure 2, hot-start performance in Figure 3, and CCA ratio comparison in Figure 4.

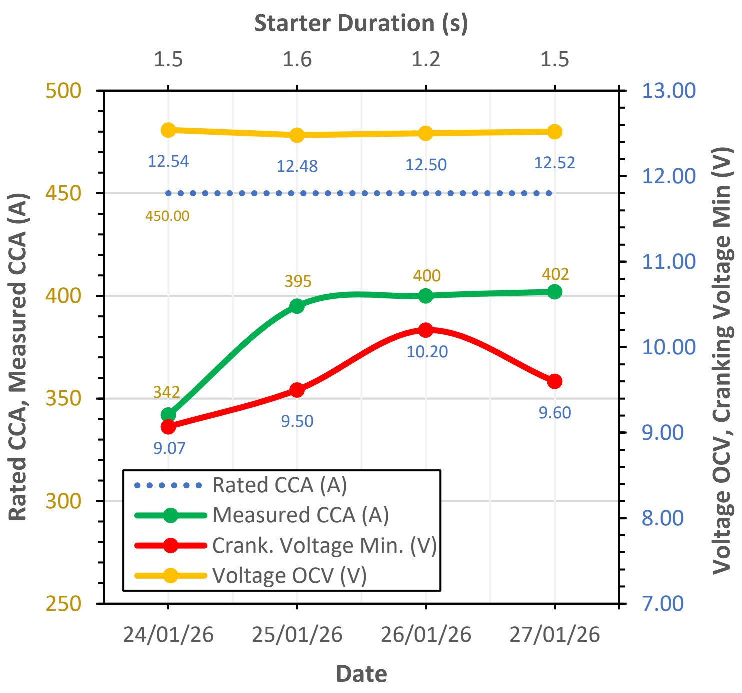

Figure 2. Cold-start battery performance based on rated CCA, measured CCA, minimum cranking voltage, OCV, and starter duration.

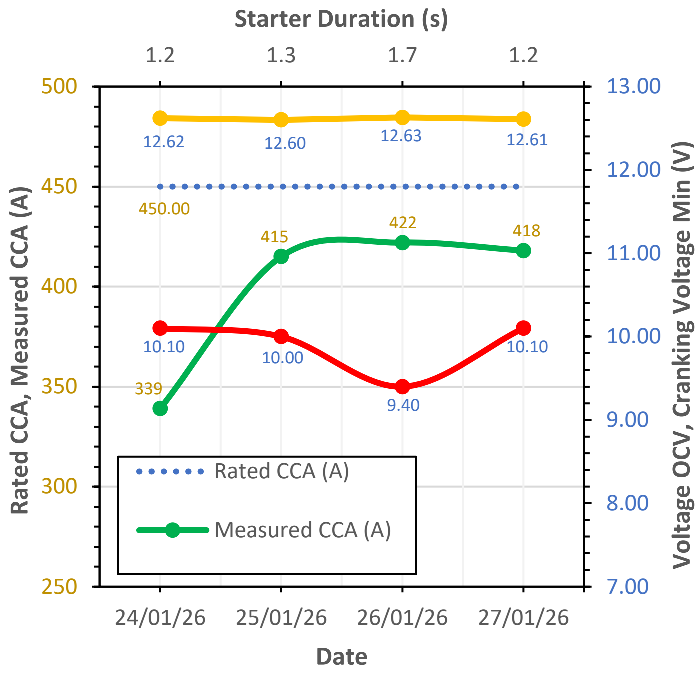

Figure 3. Hot-start battery performance based on rated CCA, measured CCA, minimum cranking voltage, OCV, and starter duration.

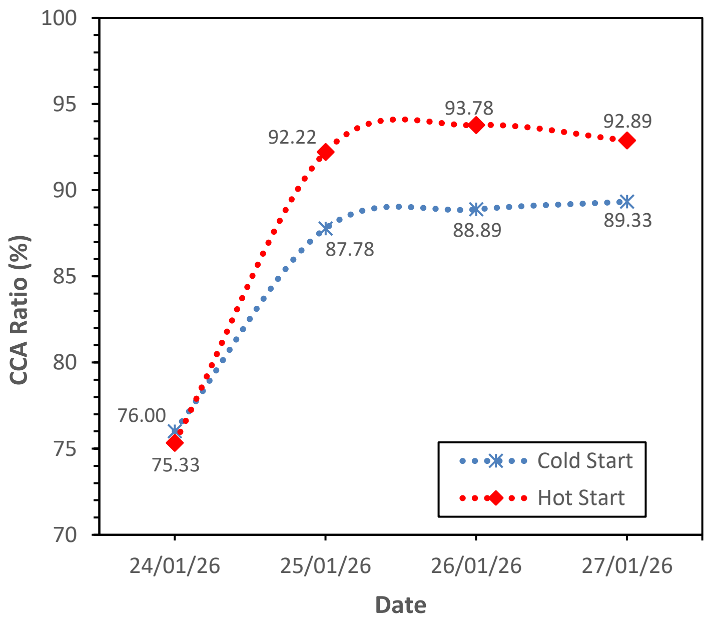

Figure 4. CCA ratio comparison between ambient cold-start and hot-start conditions.

As shown in Figure 2, the measured CCA under the ambient cold-start condition increased from 342 A on 24 January to 395 A on 25 January, 400 A on 26 January, and 402 A on 27 January. The CCA ratio in Figure 4 followed the same pattern, increasing from 76.00% to 89.33% during the observation period. The minimum cranking voltage under this condition ranged from 9.07 V to 10.20 V, while the OCV remained within a narrow range of 12.48–12.54 V. The starter duration varied between 1.2 s and 1.6 s.

Under the hot-start condition, Figure 3 shows that the measured CCA increased from 339 A on 24 January to 415 A on 25 January and reached 422 A on 26 January, before slightly decreasing to 418 A on 27 January. The corresponding CCA ratio in Figure 4 ranged from 75.33% to 93.78%, with the highest value recorded on 26 January. The minimum cranking voltage ranged from 9.40 V to 10.10 V, while the OCV remained stable between 12.60 V and 12.63 V. The starter duration under this condition ranged from 1.2 s to 1.7 s.

Overall, the measured CCA values under both operating conditions remained below the rated CCA of 450 A. However, after the first observation day, the hot-start condition produced higher measured CCA and CCA ratio values than the ambient cold-start condition. The OCV values under both conditions remained relatively stable around 12.5–12.6 V, indicating that the no-load voltage varied only slightly during the four-day observation period.

Discussion

The results show that the tested 12-V lead-acid SLI battery responded differently under ambient cold-start and hot-start vehicle operating conditions. As shown in Figure 2 and Figure 3, the measured CCA values under both conditions remained below the rated value of 450 A. However, the average measured CCA was higher under the hot-start condition, reaching 398.50 A compared with 384.75 A under the ambient cold-start condition. This pattern indicates that, within the four-day observation period, the tested battery delivered a higher short-duration cranking current under the hot-start condition. This interpretation should be limited to the tested battery because the study used only one battery unit and did not apply a controlled chamber-based temperature test.

The difference between ambient cold-start and hot-start cranking response can be interpreted through the thermal behavior of lead-acid batteries. At lower temperatures, electrolyte viscosity tends to increase, ion transport becomes less favorable, and internal resistance may rise, which can reduce the available discharge current during cranking. Conversely, warmer operating conditions may improve short-term charge-transfer activity and current delivery, although sustained exposure to heat may accelerate degradation processes. This finding is consistent with previous studies showing that lead-acid battery cranking capability and discharge behavior are affected by thermal condition and internal electrochemical response [1], [2], [9], [10]. The present study extends those findings by observing the phenomenon in a practical vehicle-based starting context rather than only through material-level or model-based battery characterization.

The CCA ratio in Figure 4 provides a clearer comparison between measured cranking capability and the manufacturer-rated specification. Under the ambient cold-start condition, the CCA ratio increased from 76.00% to 89.33%, while under the hot-start condition it increased from 75.33% to 92.89%, with the highest value of 93.78% recorded on 26 January. These results show that the tested battery operated closer to its rated cranking capability under the hot-start condition. However, the fact that the measured CCA never reached 100% of the rated value suggests that practical vehicle-based testing may differ from standardized CCA test conditions, or that the tested battery was not in an ideal new-battery condition. This interpretation is aligned with starter-battery testing standards, which treat CCA and starter-battery performance as condition-specific measurements rather than universal indicators that can be interpreted independently of test conditions [21]–[24].

Minimum cranking voltage also provides important diagnostic information because it represents the battery's ability to maintain terminal voltage while supplying high current to the starter motor. The average minimum cranking voltage was 9.59 V under the ambient cold-start condition and 9.90 V under the hot-start condition. This difference of approximately 0.31 V suggests that the voltage sag during starting was slightly lower under the hot-start condition. Previous battery measurement studies have emphasized that voltage response under load is closely related to discharge behavior, internal resistance, and battery health interpretation [4], [5], [25]. Recent vehicle-voltage measurement research also shows that battery voltage during engine start can be captured directly at the battery or through onboard diagnostic channels, but measurement method and signal location may influence the recorded voltage profile [26]. Therefore, the minimum cranking voltage in this study should be interpreted as a practical load-response indicator rather than as a complete state-of-health measurement.

The OCV pattern provides a useful contrast to the cranking-load parameters. The OCV remained relatively stable at 12.48–12.54 V under the ambient cold-start condition and 12.60–12.63 V under the hot-start condition. This narrow variation suggests that the no-load voltage condition did not change substantially during the observation period. However, stable OCV does not necessarily mean that the battery will show identical performance under starter load. OCV is often useful for supporting state-of-charge or health-related interpretation, but it cannot fully describe transient cranking response without load-based measurements [6], [7], [27]. The present findings therefore strengthen the argument that OCV should be paired with measured CCA and minimum cranking voltage when evaluating practical SLI battery starting readiness.

Starter duration further complements the electrical indicators. The average starter duration was 1.45 s under the ambient cold-start condition and 1.35 s under the hot-start condition. This shorter average duration is directionally consistent with the higher average measured CCA and higher average minimum cranking voltage observed under the hot-start condition. Nevertheless, starter duration was not perfectly proportional to CCA on every observation day. For example, Figure 3 shows that the highest measured CCA under the hot-start condition occurred on 26 January, while the starter duration on the same day was also the longest under that condition. This indicates that starter duration is not determined only by battery condition. It may also be affected by starter motor behavior, engine mechanical resistance, fuel–air preparation, ignition readiness, and other daily operational variations. Recent vehicle-starting and low-voltage battery diagnostic studies similarly indicate that cranking-related indicators should be interpreted as part of a broader starting-system response rather than as isolated battery-only variables [28]–[31].

The combined pattern across Figure 2, Figure 3, and Figure 4 shows that no single parameter fully represents SLI battery starting capability. CCA describes current-delivery capability, the CCA ratio expresses how close the measured value is to the rated specification, minimum cranking voltage describes voltage stability under load, OCV reflects no-load voltage condition, and starter duration represents the practical outcome of the starting process. Interpreting these parameters together is more informative than relying only on OCV or rated CCA. This combined approach is consistent with recent automotive battery health monitoring research, which emphasizes that in-vehicle battery diagnostics should integrate voltage response, load behavior, and degradation-sensitive indicators to detect weakening battery performance before complete failure [30]–[33].

Overall, the tested battery showed better observed cranking indicators under the hot-start condition than under the ambient cold-start condition, as reflected by higher average measured CCA, higher CCA ratio, slightly higher average minimum cranking voltage, and shorter average starter duration. However, this finding should not be generalized to all SLI batteries because the study was limited to one battery unit, four days of observation, and practical vehicle-based temperature categories. The main contribution of this study is therefore not a universal conclusion about SLI battery performance, but a practical demonstration that CCA, CCA ratio, minimum cranking voltage, OCV, and starter duration should be interpreted as interconnected diagnostic indicators. For automotive maintenance practice, this combined interpretation may help technicians distinguish whether a starting issue is more closely associated with weak current delivery, excessive voltage sag, or other starting-system factors. Future studies should involve multiple battery samples, controlled temperature measurement, instrumented starter-current recording, and longer observation periods to strengthen the diagnostic reliability of the proposed interpretation.

CONCLUSION

This study evaluated the cranking performance of a 12-V lead-acid SLI battery with a rated CCA of 450 A under ambient cold-start and hot-start vehicle operating conditions over four consecutive days. The tested battery showed better observed cranking indicators under the hot-start condition, as reflected by higher measured CCA, higher CCA ratio, slightly higher minimum cranking voltage, and shorter average starter duration. The OCV values remained relatively stable during the observation period, indicating that the differences in cranking response were not mainly associated with major no-load voltage variation. These findings show that CCA, CCA ratio, minimum cranking voltage, OCV, and starter duration should be interpreted together to obtain a more complete practical assessment of SLI battery starting readiness. The combined interpretation of these parameters can support automotive battery diagnosis and maintenance decision-making in conventional vehicle starting systems.

This study was limited to one 12-V lead-acid SLI battery tested over a four-day observation period. Therefore, the findings should not be generalized to all SLI batteries without additional testing using more battery samples. The ambient cold-start and hot-start categories were also based on practical vehicle operating conditions rather than controlled chamber testing, so the thermal condition should be interpreted as an operational category rather than a fully standardized temperature treatment. Future studies should involve multiple batteries, direct temperature logging at clearly defined measurement points, instrumented starter-current recording, and longer observation periods to strengthen the reliability and practical applicability of the diagnostic interpretation.

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