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A Misfire Detection Index for Four-Stroke Single-Cylinder Motorcycle Engines—Part II: Gap Distance and Gap Slope

***Poong Gyoo Han*[1] *and Jong Shin Lee*[1]**

[1]*Hyundai Kefico, Republic of Korea*

Abstract

Two new misfire detection indexes for single-cylinder motorcycle engines—dubbed gap distance (GD) and gap slope (GS)—are proposed in this study. GD and GS quantify the change in engine angular acceleration using the tooth time measured by the crankshaft position sensor (CKPS). GD is defined as the product of the spacing distance I (the distance from the top dead center at the explosion stroke [TDC2] to the engine speed trend line parallel to the engine speed axis) and spacing distance II (the distance from the bottom dead center at the expansion stroke [BDC2] to the engine speed trend line parallel to the engine speed axis). GS is defined as the difference between the two slopes between the engine speed inclination line and the engine speed trend line. Here the engine speed trend line connects two engine speeds at the top dead center at the intake stroke (TDC1) of the current and subsequent cycles. The GD and GS indexes can detect misfires using the engine speeds at only four teeth. The location of these four teeth could be changed to best simulate the change in engine angular acceleration for engines. The threshold range for GD and GS lies between the point where the misfire detection rate reaches 100% and the point where both the ratio of misfire detection to misfire signal (Mdtn/Msig) and the ratio of misfire signal to misfire detection (Msig/Mdtn) begin to deviate from 100%. Both GD and GS show a good misfire detection rate of approximately 99% and a perfect detection fault rate of 0% for an engine speed range of 3,000-8,000 under load conditions of over 50%. If the lower boundary limit for the load over which misfires can be accurately detected is clearly defined, a good detection rate can be achieved even under load conditions below 50%.

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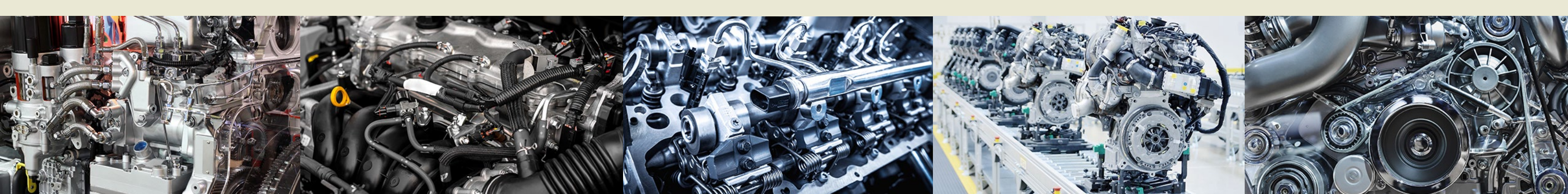


Introduction

Engine misfires can lead to increased vehicle exhaust emissions and potentially catastrophic damage to the catalyst. However, until now, misfire monitoring was not compulsory in motorcycles. Despite the wide range of research on misfire detection and diagnosis methods for multicylinder vehicle engines such as ionic current, combustion chamber pressure, and neural network methods [1, 2, 3, 4, 5], these techniques are not appropriate for low-cost motorcycles with single-cylinder engines. Therefore, we previously suggested a simple method for detecting misfires in single-cylinder motorcycle engines, termed the detrended engine rpm amplitude (DERA) index, using the tooth time measured by the crankshaft position sensor (CKPS) [6]. Building on this previous research, this study introduces two new misfire detection indexes for single-cylinder engines, the gap distance (GD) and gap slope (GS) indexes, which are simpler and a slightly more accurate than the DERA index [6], that also use engine speed derived from the tooth time. During normal combustion, the engine speed typically fluctuates substantially because of the combustion reaction energy at the explosion stroke; however, this does not occur during a misfire. Thus, GD and GS quantify the differences in the shape of the engine speed graph between normal combustion and misfires. The same experimental data used in Ref. [6] are used to verify these indexes, which indicate that GD and GS are appropriate misfire detection indexes for motorcycles with a single-cylinder engine.

Experimental Setup

Test Engine and Test Apparatus

The target motorcycle was the same as that used in Ref. [6], i.e., an Indian-made Pulsar RS 200 with a four-stroke single-cylinder engine, the specifications of which are shown in Table 1 in Ref. [6]. The same in-house engine control unit (ECU) equipped with a modified version of the misfire generator produced for multicylinder engines was used as in Ref. [6]. The misfire generator was programmed to generate single and continuous misfires. The experimental setup is shown in Figure 1 of Ref. [6]. CKPS signal data, fuel injection and ignition spark timing, and manifold absolute pressure (MAP) sensor data were measured in high resolution [6]. Engine misfire was implemented under the same two conditions: no injection of fuel ("no fuel injection") and prevention of sparking at the spark plugs ("no spark").

TABLE 1 Misfire test results according to engine load.

	No spark		No fuel injection	
Load	Engine cycles	Misfire events	Engine cycles	Misfire events
High	674	190 (28%)	487	179 (37%)
Medium	961	190 (20%)	303	136 (45%)
Low	1,272	163 (13%)	1,210	204 (17%)

Misfire Test Conditions

Both single and continuous misfires were triggered intermittently several times during each misfire test. Misfire events indicate the number of misfire-triggered cycles among the selected cycles. Misfire tests were conducted at engine speeds of 3,000-8,000 rpm every 1,000 rpm and engine load conditions of 85% (high), 50% (medium), and 25% (low) according to the injected fuel mass flow rate. After the misfire tests, sections in which misfire occurred were collected according to engine speed and engine load conditions (Tables 1 and 2, respectively). These data were then used to calculate the misfire detection rate with the use of GD and GS indexes. As the lower boundary limit of load, i.e., the boundary line above which misfire can be detected, has not yet been defined for single-cylinder motorcycle engines, it is not known whether the low-load condition value is greater than the lower boundary limit of the load. The location of this lower boundary limit may vary in the vehicle test because it could be affected by the characteristics of the engine-driveline system.

The total number of engine cycles was 4,907, and the total number of misfire events was 1,062, which represents 21.6% of all engine cycles. The percentage of engine cycles conducted at high-, medium-, and low-load conditions was 23.6%, 25.8%, and 50.5%, respectively. The rate of misfire events at different load conditions ranged from 12% to 45%. The rate of misfire events at different engine speeds from 3,000 rpm to 8,000 rpm ranged from 13% to 35%.

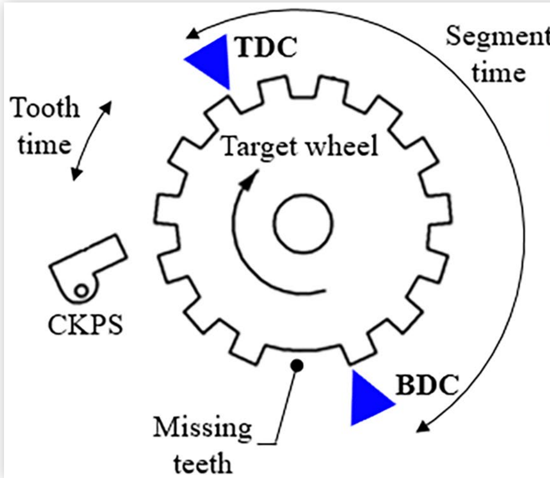
Misfire Detection Method

Target Wheel

In the single-cylinder engine of the test motorcycle, the crankshaft makes two revolutions per cycle. The target wheel also makes two revolutions per cycle with the crankshaft. The target wheel has circumferential and evenly spaced teeth in the 36-2 format (Figure 1). The synchronized position of each stroke and its tooth number are also shown in Figure 1. Two missing teeth are located immediately after the bottom dead center (BDC) point in the clockwise direction. The engine speed (rpm) at these two missing teeth is inevitably interpolated with a linear curve because engine speed reaches a significant peak at the BDC point, and a high-order polynomial cannot precisely calculate the speed at the missing teeth and their adjacent teeth.

Here TDC1 and TDC2 refer to the top dead centers at the intake and the explosion strokes in the current cycle, respectively, and TDC3 refers to the top dead center at the intake stroke in the following cycle. Moreover, BDC1 and BDC2 refer

FIGURE 1 Target wheel with 36-2 teeth.



Sync	Motorcycle	Automobile†
TDC1	Intake stroke	Cylinder 1
BDC1	Compression stroke	Cylinder 3
TDC2	Explosion stroke	Cylinder 4
BDC2	Exhaust stroke	Cylinder 2

†Firing order: 1-3-4-2

to the bottom dead centers at the compression and the expansion strokes in the current cycle, respectively. Although TDC3 is used to calculate the misfire detection index in this study, the final tooth of the current cycle can also be used instead of TDC3 to minimize the time delay between measurement and misfire diagnosis.

Figure 2 shows the CKPS, fuel injection timing, and MAP sensor data. MAP sensor data were amplified threefold to clarify the difference between intake, compression, explosion, and exhaust strokes. The intake stroke in the four-stroke engine cycle can be determined using air pressure data measured by the MAP sensor because air pressure drops instantly, creating a vacuum in the manifold, every time the intake valve is opened. Therefore, the location of TDC1, the first TDC in the current engine cycle, can be identified by the MAP sensor signal [5].

Tooth-Time Measurement

The target motorcycle uses a Hall-effect CKPS to measure the tooth time, which is described in Ref. [6]. In this study, the tooth time is defined as the time period between the current downward zero-crossing and the next downward zero-crossing of the measured CKPS signal. Figure 3 shows the engine speeds of single and continuous misfires obtained from the CKPS signals measured at 5,000 rpm, where misfires were triggered by the "no fuel injection" condition. Under normal combustion conditions, the engine speed jumped to high peaks at BDC2 immediately after TDC2. In contrast, after a misfire, the engine speed did not reach as high a peak after TDC2. The additional misfire of Figure 3(b) refers to the occurrence of a misfired cycle immediately after 10 consecutive triggered misfires despite normal fuel injection and spark conditions. This is because fuel on the inside wall of the intake manifold was blown off totally during the 10 triggered misfires; thus, normal fuel combustion did not occur afterward. Thus, eleven consecutive misfires were considered in the analysis.

TABLE 2 Misfire test results according to engine speed (rpm).

	No spark		No fuel injection	
rpm	Engine cycles	Misfire events	Engine cycles	Misfire events
3,000	185	36 (19%)	276	37 (13%)
4,000	322	76 (24%)	429	100 (23%)
5,000	592	110 (19%)	486	115 (24%)
6,000	563	111 (20%)	277	96 (35%)
7,000	648	110 (17%)	256	85 (33%)
8,000	597	100 (17%)	276	86 (31%)

Misfire Detection Indexes GD and GS

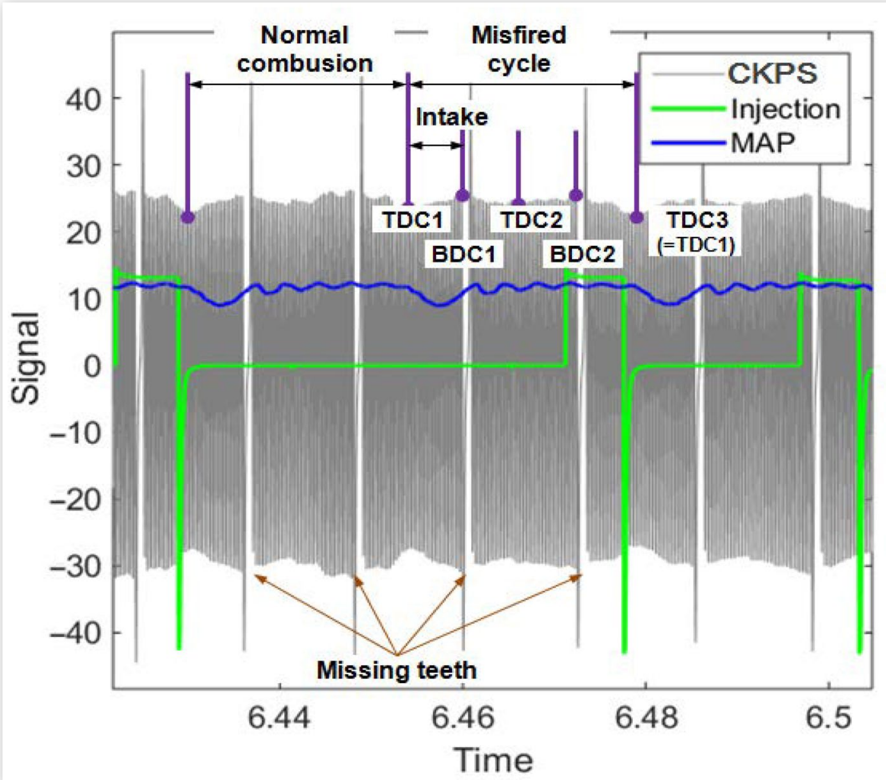
Both GD and GS detect changes in the engine speed curve to diagnose engine misfires. In a normal combustion cycle, the engine speed is greatly increased during the explosion stroke due to the combustion reaction energy, whereas a misfired cycle does not show a notable increase in the engine speed. Figure 4 presents a graphical definition of GD, which is the product of spacing distance I and spacing distance II (Equations 1-3):

$$\text{Gap distance} = \text{spacing distance I} \times \text{spacing distance II} \qquad \text{Eq. (1)}$$

$$\text{Spacing distance I} - \Delta\text{rpm}_{\text{TDC2}} = (\text{engine rpm})_{\text{TDC2}} - (\text{rpm on velocity trend line})_{\text{TDC2}} \qquad \text{Eq. (2)}$$

$$\text{Spacing distance II} = \Delta\text{rpm}_{\text{BDC2}} = (\text{engine rpm})_{\text{BDC2}} - (\text{rpm on velocity trend line})_{\text{BDC2}} \qquad \text{Eq. (3)}$$

FIGURE 2 Measured CKPS, fuel injection, and MAP sensor data.



where spacing distance I is the distance from TDC2 to the engine speed trend line parallel to the axis for engine speed and spacing distance II is the distance from BDC2 to the engine speed trend line parallel to the axis for engine speed. The engine speed trend line is a line connecting TDC1 and TDC3. GD is typically negative because TDC2 and BDC2 are located on opposite sides with respect to the engine speed trend line. Thus either spacing distance I or spacing distance II is very small during misfired cycles and GD becomes larger, i.e., the absolute value of GD decreases. A positive GD only occurs during a misfire. Therefore, if GD is larger than a selected threshold value, it can be used to indicate a misfire.

GS describes the difference between the two slopes between the engine speed inclination line and the engine speed trend line (Figure 5 and Eq. (4)), where the engine speed trend line has the same definition as that used to calculate GD. The engine speed inclination line is a line connecting BDC1 and BDC2, whose slope reflects the amount of velocity increase due to fuel combustion in each cycle. If a misfire occurs, this slope should decrease and the engine speed inclination line should become almost parallel to the engine speed trend line.

$$\text{Gap slope} = \angle\text{slope of engine speed inclination line} - \angle\text{slope of engine speed trend line} \qquad \text{Eq. (4)}$$

GS is positive during a normal combustion cycle and negative only during a misfire; thus, if GS is smaller than a selected threshold value, it can be used to indicate a misfire. Because the two spacing distances and the slope of the engine speed inclination line change between normal combustion and misfires, GD and GS can quantify the change in the engine angular acceleration to diagnose misfires in each cycle according to their threshold values. Furthermore, instead of the TDCs and BDCs used in this study, the engine speeds at different teeth can be used to obtain GD and GS if they more accurately represent the change in engine angular acceleration. This may be particularly relevant for different engines.

The misfire detection algorithm using GD and GS is shown in Figure 6. The calculation of GD and GS requires the engine speeds at four teeth among five TDCs and BDCs, respectively. Specifically, although 72-4 teeth times from the target wheel are measured per cycle at the basic software level, GD and GS use engine speeds only at TDC1, BDC1, TDC2, BDC2, and TDC3 at the application software level. Therefore, data conversion from tooth time to engine speed is required only for four teeth instead of all circumferential teeth during the signal processing. Moreover, a low-pass filter may not be required to reduce noise in the tooth time or engine speed because this filtering can distort the signal characteristics. If any filtering is necessary, the moving average can be used. Accordingly, GD and GS calculations employ simple algebraic expressions.

FIGURE 3 Engine speed (rpm) measured by the CKPS under no fuel injection conditions: (t) single misfire and (b) 10 continuous misfires.

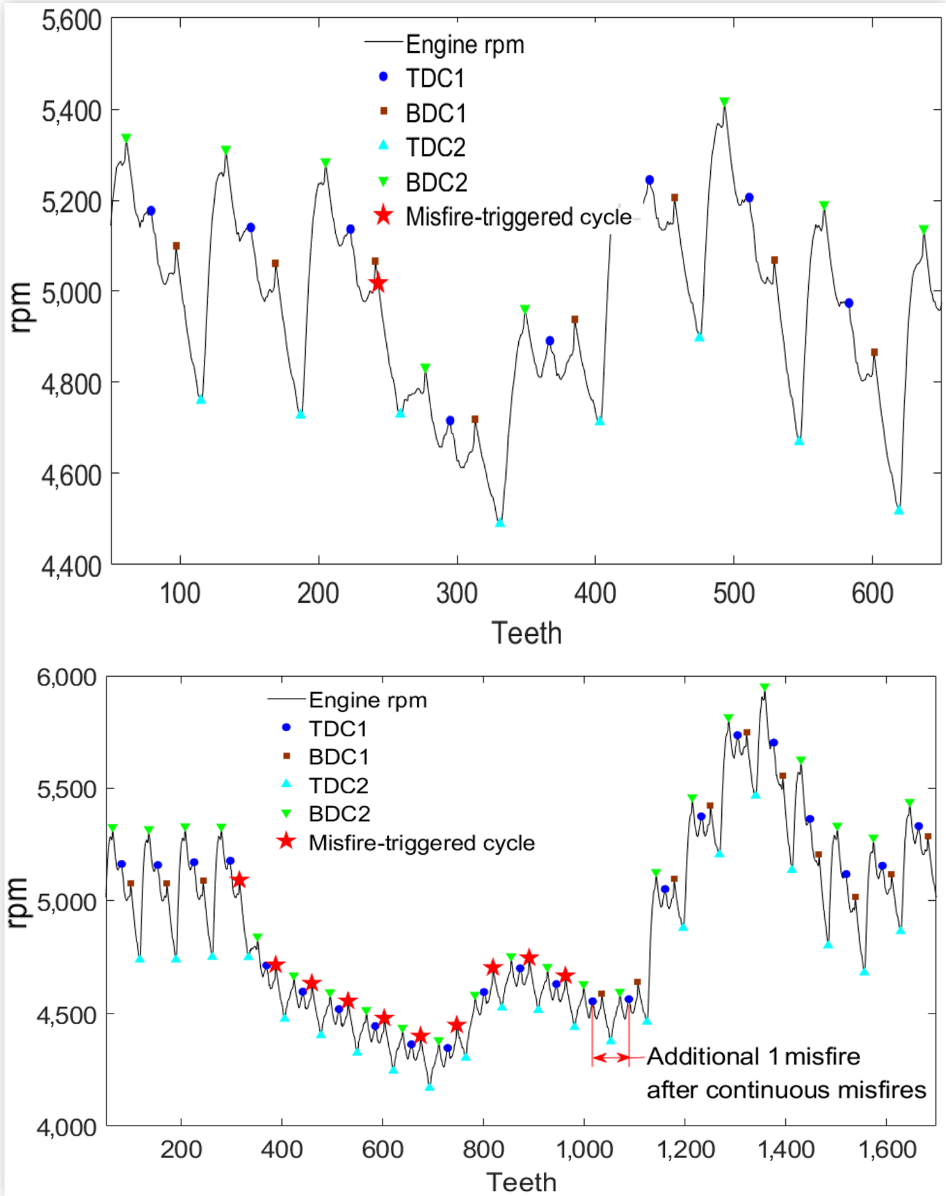


FIGURE 4 Graphical definition of GD for (l) normal combustion and (r) a misfire.

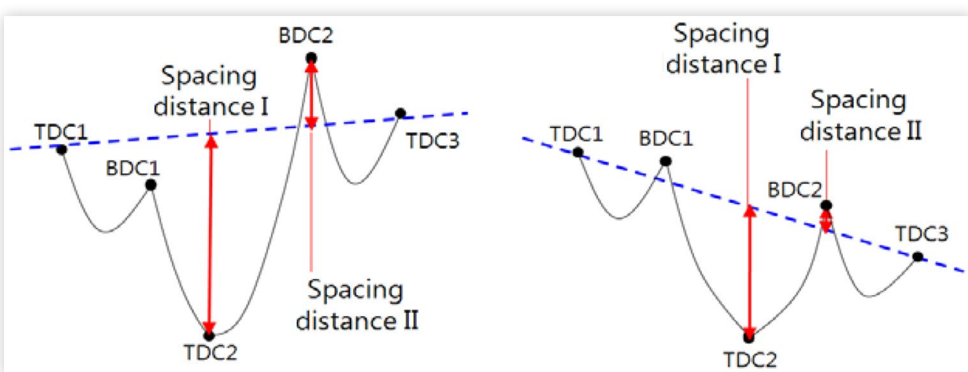
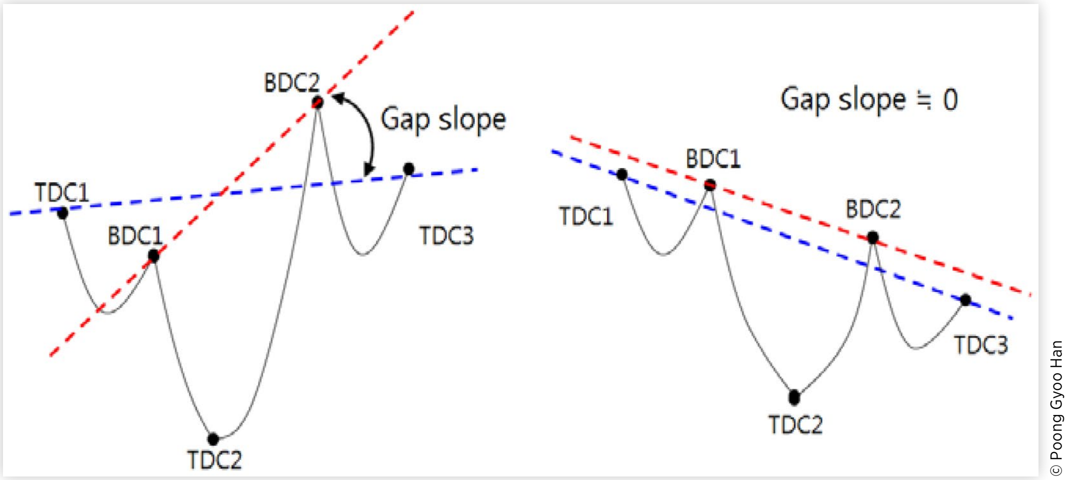
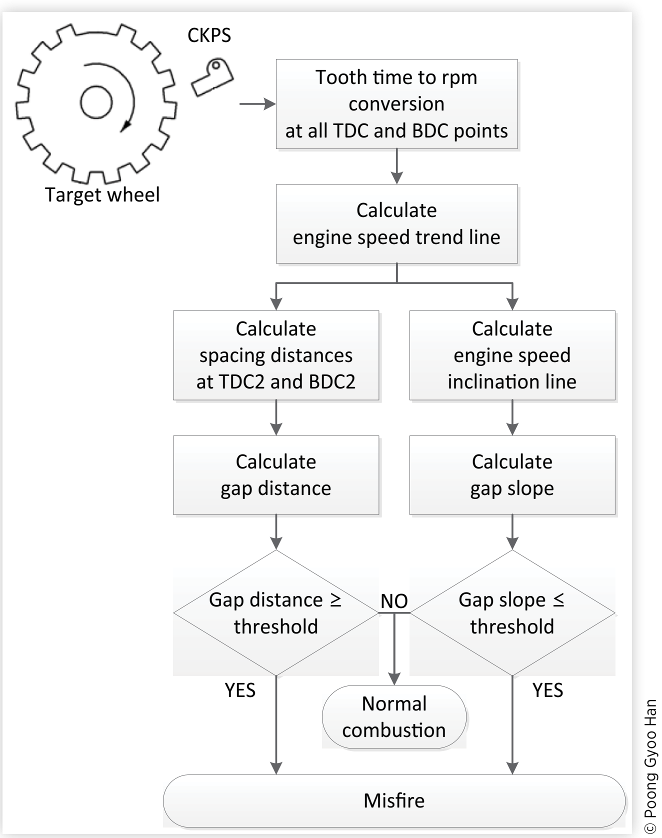


FIGURE 5 Graphical definition of GS for (l) normal combustion and (r) a misfire.



Figures 7 and 8 represent the GD and GS indexes for the engine speeds shown in Figure 3, where the red bars are triggered misfires. Both GD and GS have very distinct values for normal combustion cycles and misfires, whether single or continuous. Therefore, if adequate threshold values are selected within this margin, single and continuous misfires should be easily detected.

FIGURE 6 Procedure for detecting misfires using GD and GS indexes.



Threshold

Figure 9 shows two detection rates for the complete range of engine speeds, i.e., the ratio of misfire detection (Mdtn) to misfire signal (Msig) and ratio of Msig to Mdtn, under medium-load conditions for GD and high-load conditions for GS. The solid line represents the Mdtn/Msig ratio, which indicates the number of misfires detected compared to the number of misfires triggered at a certain engine speed. This detection rate increases to 100% before beginning to deviate after a certain value as the threshold value changes. The dotted line represents the Msig/Mdtn ratio, which indicates the number of triggered misfires detected compared to the number of misfires detected at a certain engine speed. This detection rate remains at 100% before beginning to deviate as the threshold value changes. This means that all misfire signals are detected as misfires and that there are no detection faults in this study, whereby normal combustion cycles are detected as misfired cycles.

Unlike these two detection rates, the misfire detection rate is the ratio of misfires detected among all misfire signals. Thus, before the misfire detection rate reaches 100%, it is the same as the Mdtn/Msig ratio; however, once it reaches 100%, the misfire detection rate stays at 100%. Therefore the threshold should be selected in the range from where the misfire detection rate reaches 100% to where both the Mdtn/Msig ratio and Msig/Mdtn ratio begin to deviate from 100% according to the engine speed. These results are the same for both GD and GS, as shown in Figure 9.

Misfire Detection Rate

GD and GS obtained from the test conditions in Table 1 and Table 2 are shown in Figures 10-12. The misfire detection results using GD and GS under both high- and medium-load conditions are shown in Figures 10 and 11, respectively. Both

FIGURE 7 GD index at 5,000 rpm and high-load conditions for the data in Figure 3: (t) single misfire and (b) continuous misfires.

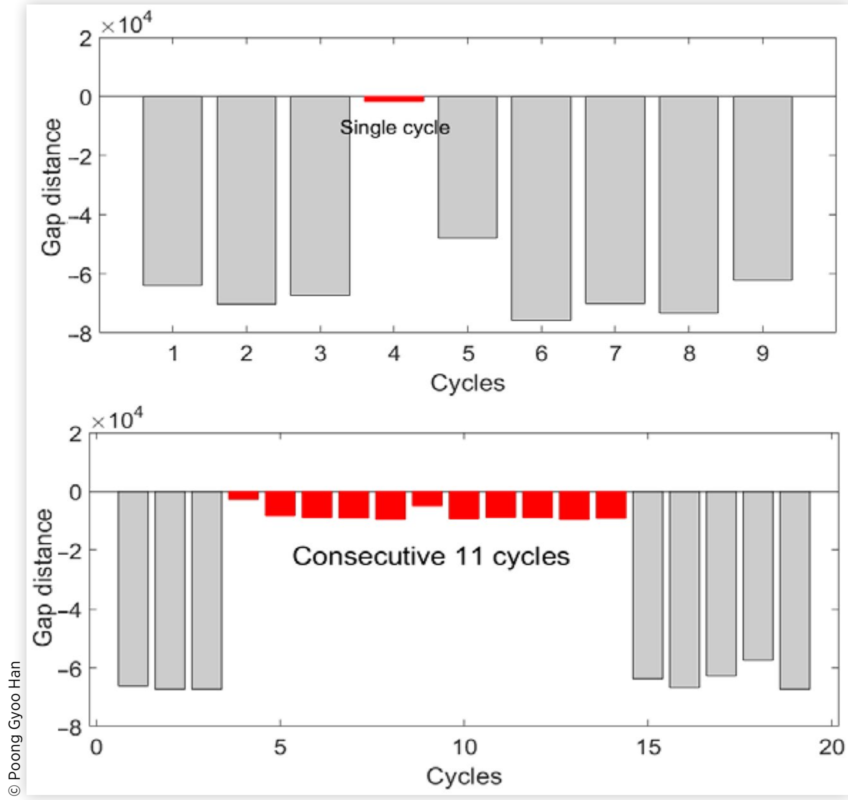


FIGURE 8 GS index at 5,000 rpm and high-load conditions for the data in Figure 3: (t) single misfire and (b) continuous misfires.

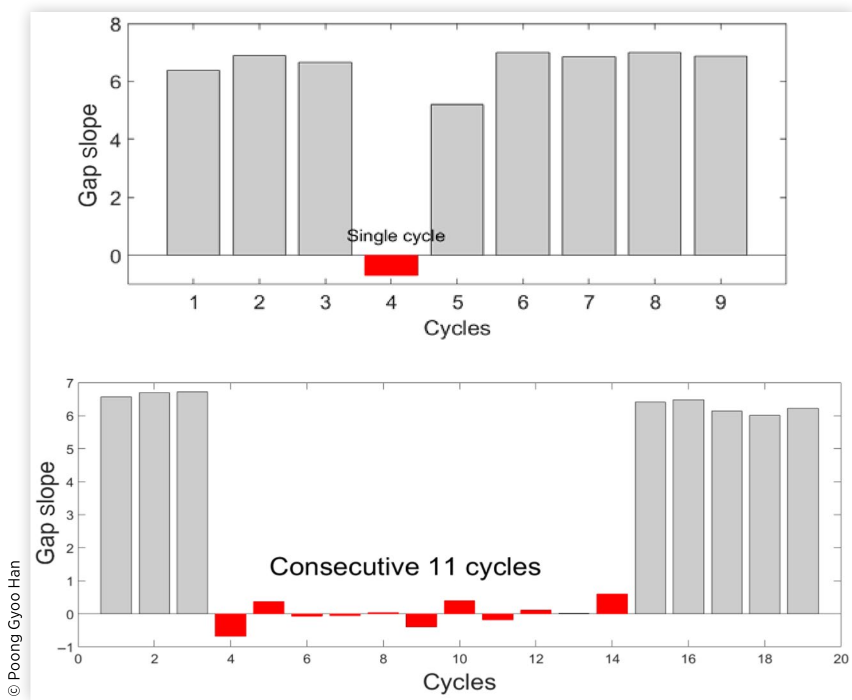


FIGURE 9 Detection rates over the entire speed range: (t) GD under medium-load conditions and (b) GS under high-load conditions.

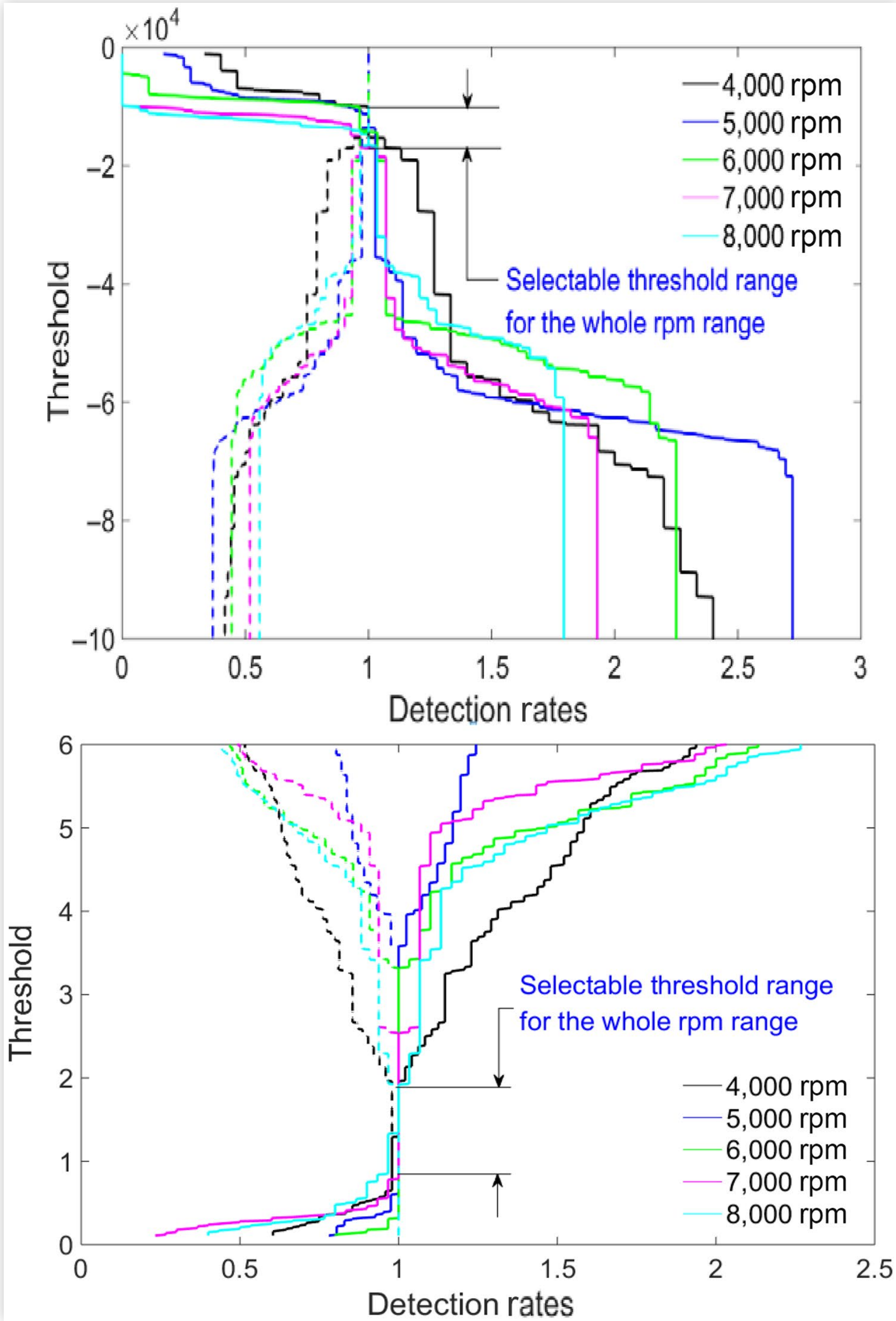
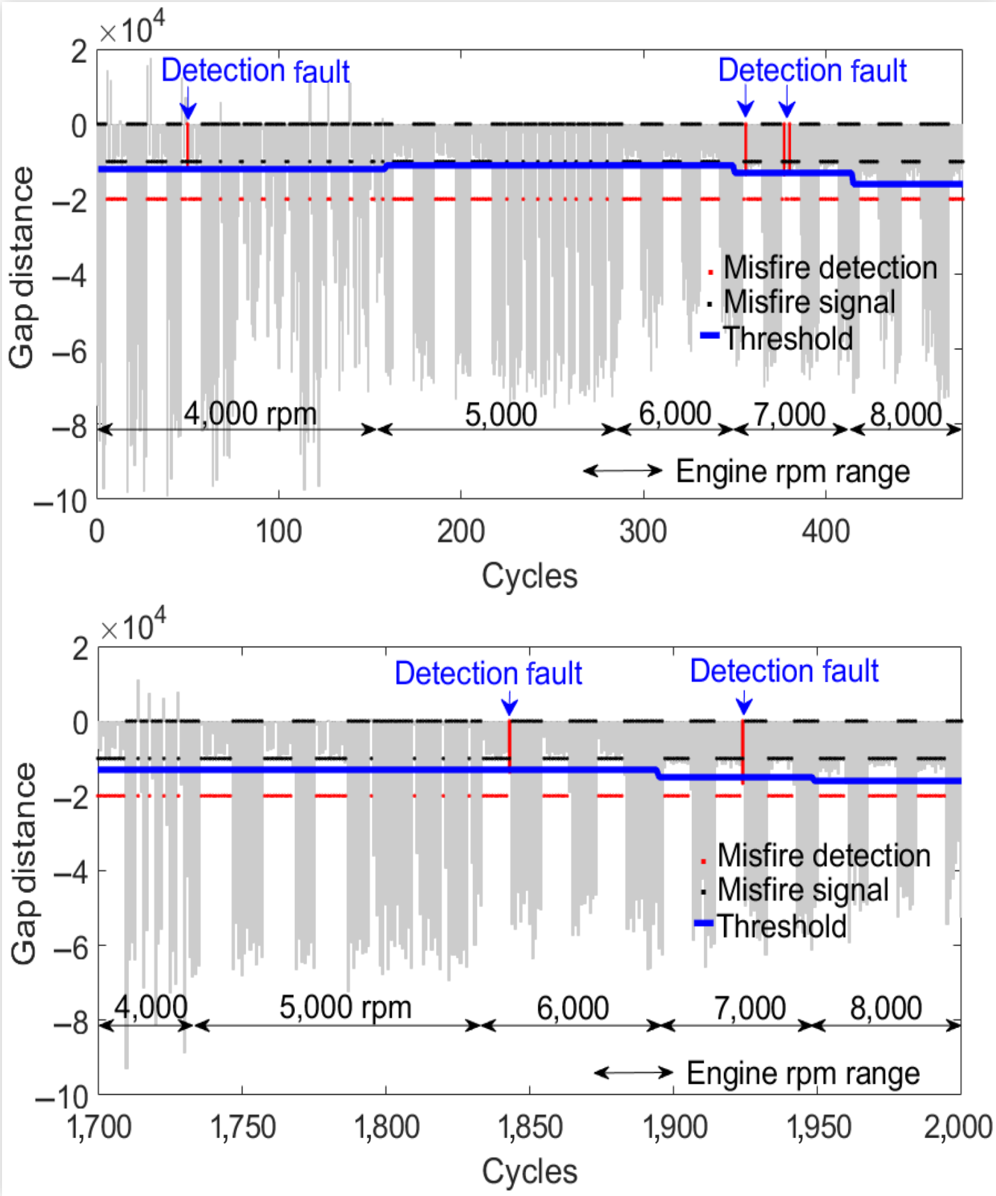


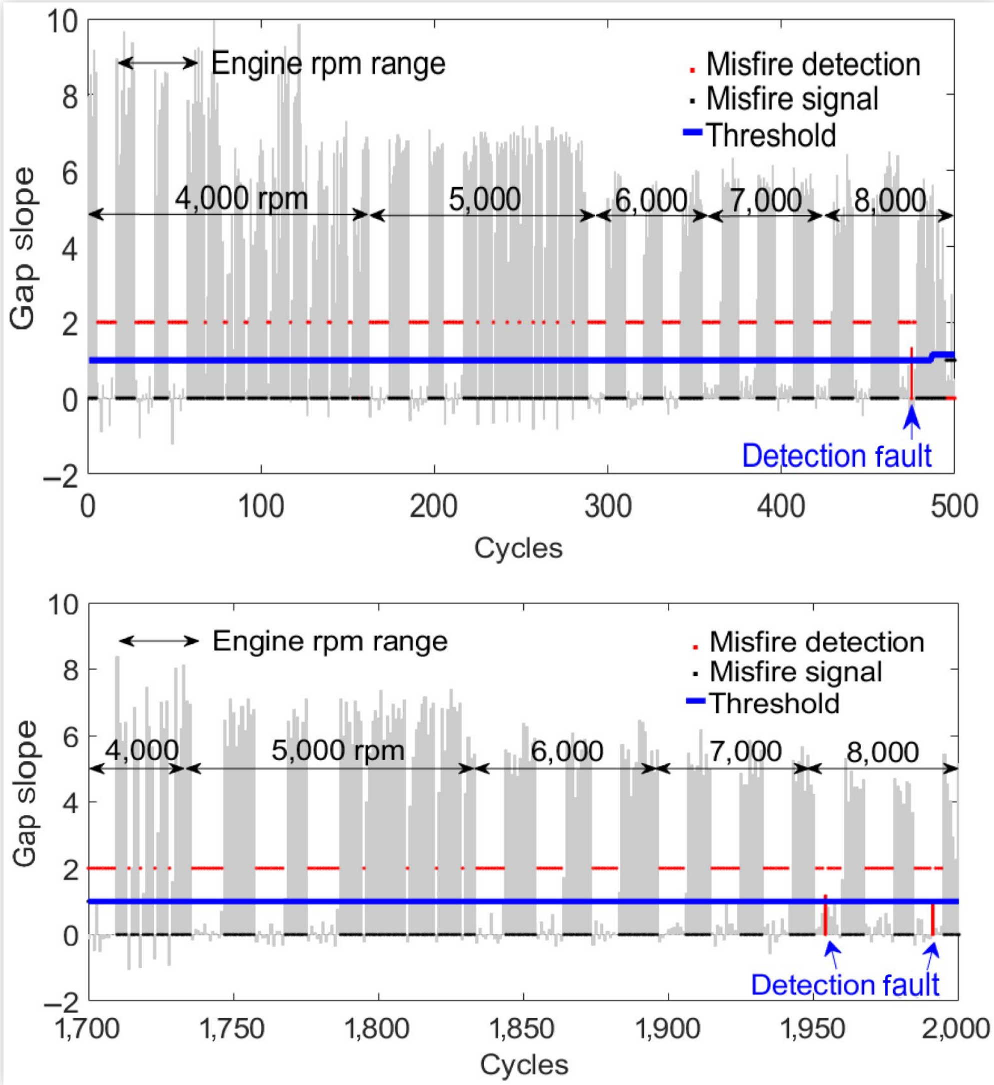
FIGURE 10 GD under (t) high-load and (b) medium-load conditions with "no fuel injection."



GD and GS detect the majority of all triggered misfires as misfire events under the two load conditions. Only nine detection faults exist: five for GD and four for GS. In six of the nine cases, the misfire signal should be considered as normal combustion, which is caused by dynamo operation, whereby the engine speed falls below a predetermined value and is then returned to the preset speed condition by the dynamo. This is not a real detection fault; therefore, three of the nine detections faults indicate normal combustion detected as a misfire. Two of the three detections occurred immediately after the 11 consecutive misfires in the two continuous misfire conditions for GD. It is suggested that the effect of 10 consecutive misfires influenced two cycles immediately after the continuous misfires. Only one case among these three detections occurred during normal combustion for GS. Therefore, it is inferred that GD and GS exhibit good misfire detection performance in single-cylinder engines.

Figure 12 shows the misfire detection results using GD and GS under low-load conditions. Triggered and detected misfires are plotted together for GD and GS at two engine speed conditions of 3,000 rpm and 8,000 rpm in order to compare the difference in misfire detection rates at different engine speeds. Triggered misfires are indicated by red bars and detected misfires are indicated by blue (GD) and green (GS) bars. The many detection faults at both high and low engine speeds under low-load conditions are thought to be because the low-load value is near to or below the lower boundary limit for the load. Specifically, detection faults

FIGURE 11 GS under (t) high-load and (b) medium-load conditions with "no fuel injection."



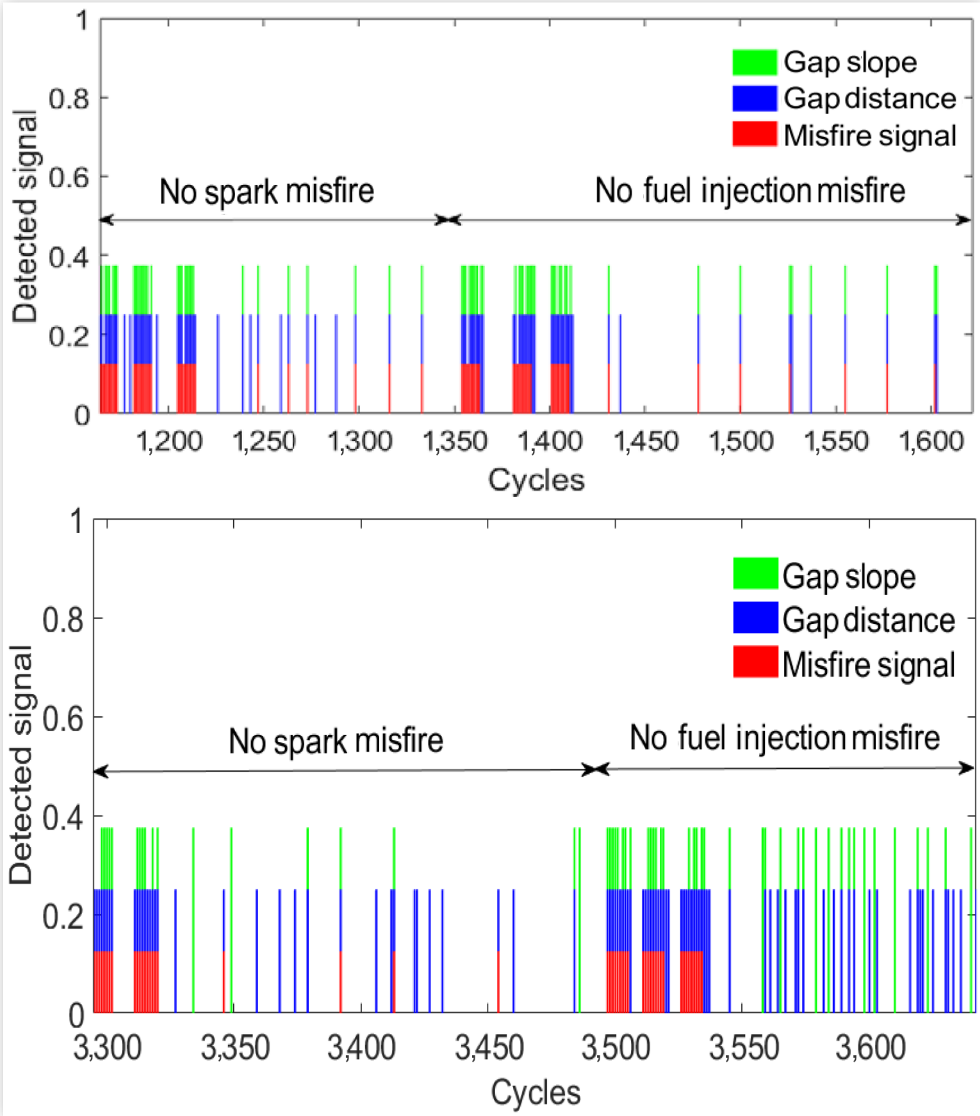
increase at higher engine speeds under low-load conditions because some normal combustion cycles are also detected as misfires at 3,000 rpm, whereas the detection fault rate of normal combustion is higher, and some misfire signals cannot be detected at 8,000 rpm. This result is similar to that for vehicles with multicylinder engines.

Misfire Detection Strategy

The misfire detection rates and detection fault rates for normal combustion cycles in Figures 10-12 are summarized in Figure 13, where H, M, and L represent high-, medium-, and low-load conditions, respectively, and "&", "~", and "/" symbols indicate the AND Boolean operator, NOT Boolean operator, and division operator, respectively. Figure 13 also includes the detection rates of the DERA index for comparison [6]. Under high- and medium-load conditions, GD and GS exhibit high misfire detection rates of approximately 99%, which are slightly more accurate than those of the DERA index. In addition, the detection fault rate of normal combustion is zero. However, under low-load conditions, both the misfire detection rate and detection fault rate of normal combustion are reduced. This is because the low-load value is thought to be near to or below the lower boundary limit for the load. If the load is over this lower boundary limit, both the misfire detection rate and detection fault rate of normal combustion are expected to be as good as those under high- and medium-load conditions.

The principal characteristics of GD, GS, and DERA are compared in Table 3. Detrending is not necessary for GD, and this index is more effective than GS and DERA. GS indicates detrending by the engine speed trend line at two specified

FIGURE 12 Misfire detection results of GD and GS under low-load conditions at (t) 3,000 rpm and (b) 8,000 rpm.



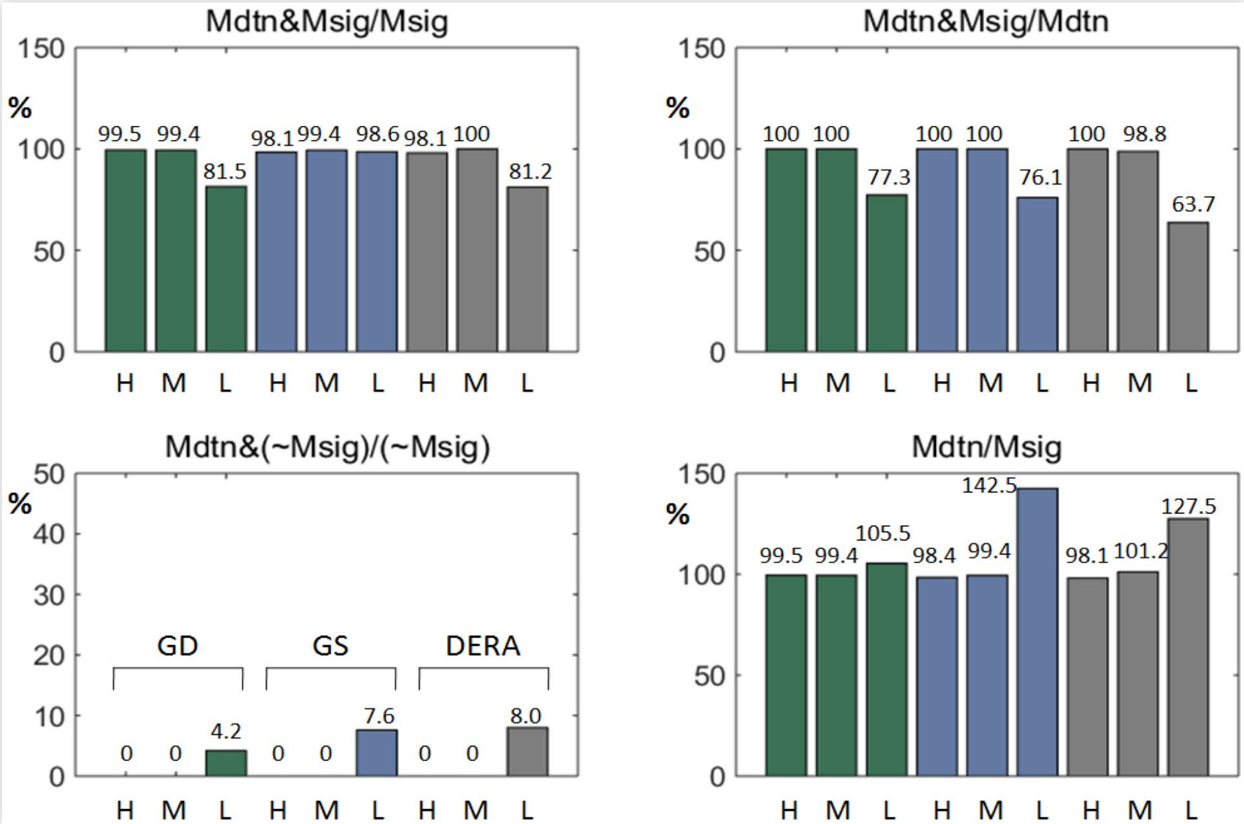
teeth, which are BDC1 and BDC2 in this study. Thus, if the engine speed is detrended by the engine speed trend line, the three indexes have almost the same effectiveness with respect to detrending. It follows that the calculation procedure of all three indexes is simple, and they have a similar calculation time and load for detecting misfires. On the contrary, it can be judged that the detection performance of the three indexes is high because their misfire detection rates are larger than 98%. As the detection rate of GS and GD are slightly higher than that of DERA under the high- and medium-load conditions and the detection fault rate of GD is almost half of that of GS and DERA under the low-load condition, GD can be evaluated as being the best among the three indexes.

As well as the good individual misfire detection performances of GD and GS, these two methods can be used together with their AND or OR Boolean operators according to the specific misfire diagnosis strategy because their calculation procedure is simple and partly shared. Specifically, the AND operator combination could be used to minimize the detection fault rate of normal combustion, whereas the OR operator combination could maximize the misfire detection rate. Future work is required to validate the benefits of combining these indexes and operators.

Conclusion

Two new misfire detection indexes, GD and GS, were proposed to quantify the changes in the angular acceleration of the engine per cycle. The GD and GS indexes use existing tooth-time data measured by CKPS; hence, there is no additional cost, as compared with the DERA index [6]. The GD index is defined as the product of the spacing distance I and spacing

FIGURE 13 Detection rates for GD and GS with DERA.



distance II (where spacing distance I is the distance from TDC2 to the engine speed trend line parallel to the engine speed axis, and spacing distance II is the distance from BDC2 to the engine speed trend line parallel to the engine speed axis). The GS index is defined as the difference of the two slopes between the engine speed inclination line and the engine speed trend line. The thresholds for GD and GS can be determined within the range from where the misfire detection rate reaches 100% to where the Mdtn/Msig and Msig/Mdtn ratios begin to deviate from 100%. After analyzing the tooth-time data obtained from misfire tests on a four-stroke single-cylinder motorcycle engine, the following conclusions were drawn from this study.

1. GD and GS indicate a misfire detection rate of more than 99% under high- and medium-load conditions, i.e., where the load values exceed the lower boundary limit for loads in the range of 3,000-8,000 rpm. The detection fault rate of normal combustion is zero under the same conditions.
2. The GD and GS methods further simplify the misfire detection procedure because calculating the GD and

TABLE 3 Comparison of the characteristics of GS, GD, and DERA.

	GS		GD	DERA	
Detrending	○		X	○	
Used teeth	4[1]	All[2]	4	4	All[3]
Calculation time and load	Small	Large	Small	Small	Larger
Detection rate	Higher[4]		Higher[4]	High	

[1] Detrending by the engine speed trend line.
[2] Detrending by the linear regression method. This condition is not dealt with in this study.
[3] Detrending by the linear regression method and detection of minimum and maximum values among the engine speeds at all teeth.
[4] The detection rate of GS and GD is slightly higher than that of DERA (see Figure 13).

GS indexes includes the detrended effect for engine speed, unlike the DERA index.

3. The GD and GS indexes can detect misfires using engine speeds only at four teeth. If two of these teeth can be chosen from the teeth other than BDC1 and BDC2 to best simulate the change in the slope of the engine speed inclination line, these two indexes could diagnose misfires even if the number of teeth on the target wheel becomes smaller. Further studies will be conducted on this.

Contact Information

102, Gosan-ro, Gunpo-si, Gyeonggi-do, 15849, Korea
Engine Control Design Team, Hyundai Kefico
pghan@hyundai-kefico.com
pghan@hanmail.net

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Abbreviations

BDC - Bottom dead center
CKPS - Crankshaft position sensor
DERA - Detrended engine rpm amplitude
ECU - Engine control unit
GD - Gap distance
GS - Gap slope
PC - Personal computer
TDC - Top dead center

Definitions

& - Boolean AND operator
~ - Boolean NOT operator
/ - Division operator
(b) - Bottom as the suborder for graphs
(l) - Left as the suborder for graphs
(r) - Right as the suborder for graphs
(t) - Top as the suborder for graphs
H - High
L - Low
M - Medium
Mdtn - Detected misfire event
Msig - Misfire signal

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