Dynamic coordinated control of a downhill safety assistance system for hybrid electric buses

Zhaobo Qin, Donghao Zhang, Yunwu Han and Yugong Luo

Abstract
When driving downhill, downhill safety assistance control can ensure a safe speed. A downhill safety assistance system was developed by our research group to help hybrid electric vehicles to maintain a stable speed when driving downhill. For hybrid electric buses, in addition to the pneumatic braking system, the motor can quickly provide an electrical braking torque, and the engine can be considered a mechanical brake. The downhill safety assistance system for hybrid electric buses maintains the desired downhill speed on different road slopes. However, when and how to activate or deactivate the downhill safety assistance system because of the driver's operation or the road conditions was not discussed in combination with the energy management strategy for the vehicle. Additionally, there is currently no dynamic control strategy for the transition process when the braking modes of the downhill safety assistance system change, which can lead to instability. To address the limitations of previous studies, a dynamic coordinated control strategy of the downhill safety assistance system is proposed considering practical application, which focuses on the above two aspects to keep the entire system stable. To improve the ride comfort and the vehicle safety when the downhill safety assistance system works in conjunction with the energy management strategy for the vehicle, the proposed control strategy is developed to activate or deactivate the downhill safety assistance system based on the driver’s driving habits and operation and the road conditions in order to reduce the workload and to improve the driveability of the buses. To maintain the ride comfort during the transient process of shift in the braking mode and to maintain a stable speed over the overall course, the mode-shift coordinated control strategy of the downhill safety assistance system is presented, which combines the braking modes to ensure that the braking torque changes steadily without saltation. The experimental results validate the performance of the entire dynamic coordinated control strategy of the downhill safety assistance system with a high stability, and the statistics demonstrate that the downhill safety assistance system obviously improves the fuel economy and reduces the driver workload.

Keywords
Downhill safety assistance system, hybrid electric buses, dynamic coordinated control strategy, vehicle safety, fuel economy, driver workload

Introduction
When driving downhill on a long steep slope, vehicle brake systems are important for preventing vehicles from accelerating too quickly. This is especially important when buses with passengers drive on downhill roads. Therefore, the speed should be maintained within certain ranges for safe downhill driving using a reliable brake system. In contrast with the hydraulic brake systems in cars, buses usually use pneumatic brake systems to provide high brake forces for a long time. For buses using only an internal-combustion engine (ICE) for propulsion, several brake systems have been introduced, namely engine brake systems, exhaust brake systems and retarder brake systems. Engine brake systems provide a limited braking torque, which is influenced by the operating speed and the gear ratio with a low accuracy. Exhaust brake systems, which can be used with diesel engines, provide a continuous braking force within certain gradients to improve...
the brake reliability but cannot accurately control the torque. Retarder brake systems can be divided into two types: eddy current retarders and hydraulic retarders. Retarder brake systems have slow responses and can lead to heat recession after operating for long times.\textsuperscript{5,6} The engine and retarder auxiliary braking systems generate a nearly constant braking torque only during downhill driving, which limits improvements to the downhill safety performance. Because of the disadvantages of these brake systems, there has been no automatic downhill assistance method for ICE buses, as the speed cannot be controlled accurately and rapidly for long times. However, a hill descent control system must be activated manually without considering the driving conditions, which can operate only at low speeds and can cause heat recession during long downhill descents.\textsuperscript{7}

Because electric motors have quick response times, considerable research has been conducted into the development of a braking strategy based on torque optimization for electric vehicles.\textsuperscript{5,9} Some papers have proposed control strategies for electric vehicles when driving downhill which operate by adjusting the electric motor torque.\textsuperscript{10,11} Sway-Tin et al.\textsuperscript{12} provided a method that helped a driver to drive normally on a long downhill road by removing his or her foot from the pedal to adjust the vehicle speed. The system also extended the driving range of the hybrid electric vehicle (HEV) by converting the braking energy into stored electric energy using the electric motor. However, different driving habits and operations were not considered, and a braking torque based on only the road grade was not reasonable, as it had limitations for practical use. Our research group first proposed the downhill safety assistance system (DSAS) for HEVs. This system consists of three main subsystems, namely vehicle braking (hydraulic braking or pneumatic braking), electric motor braking and engine braking. Luo et al.\textsuperscript{13} established a driver’s downhill intention model and proposed a control strategy for the DSAS in terms of the braking torque.\textsuperscript{13} In the system, the braking modes shown above formed the DSAS, which is effective across the full range of speeds to improve the vehicle safety and the ride comfort. The DSAS was certified to have a good performance when driving downhill, but mode changes were not described and situations in which the accelerator pedal or the brake pedal was engaged were not considered.

As an auxiliary function of vehicles, the ability to cooperate with the main control strategy must be well developed owing to possible changes in the driver’s operation or the road conditions. Additionally, the transient process between the modes should also be kept smooth. Researchers have investigated the join between the auxiliary function and the main control strategy and have also presented the transition strategy if the function has several modes.\textsuperscript{14,15} Benalie et al.\textsuperscript{16} improved the adaptive cruise control system based on the speed characteristics, which merged brake control and velocity control together to control the speed to any desired speed without jerk or steady-state error. The system allowed the driver to take control of the vehicle at any time. Bageshwar et al.\textsuperscript{17} proposed an optimal control strategy using model predictive control for transitional manoeuvres of vehicles with adaptive cruise control, which can establish a steady-state following distance behind a newly encountered vehicle with a slower speed. However, a control strategy for activating or deactivating a DSAS which cooperates with the vehicle energy management strategy has not yet been developed. Additionally, a control strategy for a transient process which can ensure a smooth mode shift has also not yet been proposed.

In this paper, we established the dynamic coordinated control strategy of the DSAS more comprehensively than in previous studies. In summary, the main contributions are as follows.

1. To maintain the ride comfort and the vehicle safety using the DSAS in conjunction with the vehicle energy management strategy, the control strategy for activating or deactivating the DSAS owing to the changes in the driver’s operation or the road conditions is developed to determine when and how the DSAS works.
2. To improve the performance and to ensure a smooth switch during the transient process, a mode-shift coordinated control strategy is presented to ensure a steady braking torque with gradual changes to keep the vehicle speed stable without saltation.

This paper is structured as follows. The second section introduces the structure and characteristics of our research object. The third section describes the operating modes of the DSAS in terms of the braking torque calculating theory. In the fourth section, we show the control strategy for activating and deactivating the DSAS. The fifth section focuses on the control strategy of the transient process during mode shifts. The sixth section gives the results of the road experiments to validate the performance of the DSAS, and conclusions are drawn in the seventh section.

**Brief introduction of the research object**

The research object is a hybrid electric bus (HEB), which adopts the series–parallel configuration shown in Figure 1. Also, the bus is a plug-in hybrid type which provides drivers with more choices.

Two electric motors are used. The front electric motor connected to the engine is used to start the engine and to generate electricity when the state of charge (SOC) is low. The rear electric motor provides the driving torque and regenerates energy when braking. The energy management strategy has five main modes: pure electric mode, series mode, engine-drive...
According to the accelerator pedal position \( v_{brk} \) and the current speed \( v \), the braking torque \( T_{brk} \) of the electric motor and the braking torque \( T_{eng} \) of the engine, there are six operating modes for the DSAS.

The four braking modes are the coasting braking mode, the electric motor braking mode, the engine braking mode and the electric motor and engine coordinated braking mode. Two additional modes operate when the driver engages the accelerator pedal or the brake pedal. The mode types are shown in Table 1 and are described as follows.

1. **Accelerating demand mode (mode 1) and decelerating demand mode (mode 2).** Mode 1 operates when the driver engages the accelerator pedal to increase the speed. Similarly, mode 2 operates when the driver wants to slow down and engages the brake pedal.

2. **Coasting mode (mode 3).** For HEVs, in addition to the mechanical braking, electric motors always provide a negative braking torque when coasting and with the brake pedal engaged in order to make full use of the braking energy.\(^{19,20}\) The electric motor torque when decelerating or coasting is denoted as \( T_{m,brk} \), which is related to the vehicle speed \( v \) and the brake pedal position \( P_b \). The function \( f(v) \) is related to the current speed, which is determined according to the external characteristic curve of the motors. \( c \) is a constant which is not 0. When the accelerator pedal and the brake pedal are both released, which means that \( P_a = 0 \) and \( P_b = 0 \), mode 3 is initiated, and because

\[
T_{m,brk} = (P_b + c)f(v)
\]

the coasting braking torque is given by

\[
T_{coast} = cf(v)
\]

3. **Electric motor braking mode (mode 4).** To maintain a constant speed when driving downhill, if the SOC is below a threshold value, mode 4 operates and can provide a large torque over a short time with a high accuracy.\(^{21}\) The system uses proportional–integral–derivative (PID) control to achieve a good performance. The calculation function is

\[
T_{sum} = (K_P + K_I s^{-1} + K_D s)(v_{ini,\tau} - v_t)
\]

where \( K_P \) is the proportional function, \( K_I \) is the integration parameter, \( K_D \) is the differential parameter, \( v_{ini,\tau} \) is

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**Operating modes of DSAS for HEBs**

The integrated control strategy of the DSAS is given in Figure 2 to address the overall system. The details are as follows.

The integrated control strategy in Figure 2 is composed of two main parts, namely the downhill safety assistance modes and the relation between the main energy management control strategy and the DSAS. According to the accelerator pedal position \( P_a \), the brake pedal position \( P_b \) and the current speed \( V \), activating or deactivating the DSAS is determined in cooperation with the main control strategy. Also, on the basis of the SOC of the battery, the error \( \Delta V \) in the vehicle speed, the braking torque \( T_M \) of the electric motor and the braking torque \( T_{eng} \) of the engine, there are six operating modes for the DSAS.

![Figure 1. Main powertrain of the HEB.](image-url)

**Table 1. Mode types.**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Accelerating demand</td>
</tr>
<tr>
<td>2</td>
<td>Decelerating demand</td>
</tr>
<tr>
<td>3</td>
<td>Coasting braking</td>
</tr>
<tr>
<td>4</td>
<td>Electric motor braking</td>
</tr>
<tr>
<td>5</td>
<td>Electric motor and engine coordinated braking</td>
</tr>
<tr>
<td>6</td>
<td>Engine braking</td>
</tr>
</tbody>
</table>

**Figure 2.** The integrated control strategy of the DSAS.
the speed at the initial time (when entering this mode) and \(v_t\) is the speed at the current time. \(K_P\) is a function of the speed difference \(v_{ini} - v_r\). As the difference increases, \(K_P\) increases simultaneously to reduce the speed difference rapidly. In this mode, the total braking torque \(T_{total}\) for the DSAS, which is equal to the motor torque \(T_M\), is

\[
T_{total} = T_M = T_{sum} \quad (3)
\]

4. **Engine braking mode (mode 6)**. When the SOC has reached a threshold value and the battery cannot store any energy, the engine braking mode operates. If the engine is not operating, it needs to be connected to the powertrain by engaging the clutch to provide the engine braking torque. When entering mode 6, the engine should match the rotational speed of the rear electric motor, which requires a speed regulation process. This process can result in interruption if the speed does not match very well. Thus, the speed regulation process is designed as shown in Figure 3, which can ensure a smooth transition. The clutch is engaged when the difference between the engine speed \(\omega_e\) and the rear motor speed \(\omega_r\) is within 5 r/min for 10 periods. To attain a fast and smooth process, speed regulation lasted another five periods as the clutch starts to be engaged. When the clutch is engaged, the engine can provide a braking torque \(T_{eng,b}\) according to

\[
T_{total} = T_{eng,b} \quad (4)
\]

5. **Electric motor and engine coordinated braking mode (mode 5)**. When the desired motor torque is so high that it nearly exceeds the motor torque range, which would result in an increase in the vehicle speed, the electric motor and engine coordinated braking mode provides a higher braking torque. This mode also requires the speed regulation process, except when shifting from mode 6. Thus, the
from increasing. In the previous strategy,\textsuperscript{13} if the brakes think that it is necessary to prevent the vehicle speed constant when travelling downhill. Therefore, all drivers pedal to ensure safety even though the speed remained indicate that most drivers step lightly on the brake habits and the situations above, which can help the DSAS and the energy management strategy

\textbf{Activation and deactivation control strategy of the DSAS}

Activating or deactivating the DSAS depends on the road conditions or the driver's operation. The control strategy is shown in Figure 2, which shows when and how to activate or deactivate the system. The system should give priority to the driver's operation of the accelerator pedal and the brake pedal considering his or her driving habits. Also, the transient process should ensure a continuous torque change between the DSAS and the energy management strategy.

\textbf{Activating the DSAS}

When driving downhill, as the speed increases and the driver does not engage the accelerator pedal nor the brake pedal, the DSAS engages, which is the previous condition described by Luo et al.\textsuperscript{13} It first operates in mode 3, namely the coasting mode. If the speed continues to increase rapidly after the coasting motor torque is applied, it enters mode 4, namely the electric motor braking mode. Then, the mode can shift as the vehicle state changes.

However, an investigation was performed using bus drivers. We chose 24 experienced bus drivers and two questions were asked, as listed in Table 2. The results indicate that most drivers step lightly on the brake pedal to ensure safety even though the speed remained constant when travelling downhill. Therefore, all drivers think that it is necessary to prevent the vehicle speed from increasing. In the previous strategy,\textsuperscript{13} if the brake pedal is engaged, the DSAS is deactivated, which can cause speed saltation as the braking torque changes.

In our control strategy, we consider the driving habits and the situations above, which can help the driver to maintain a stable speed when engaging the brake pedal. There are two main advantages of providing additional torque when the normal braking torque is not able to maintain the speed. First, it assists with a sufficient braking torque if the vehicle accelerates with the brake pedal engaged, which can reduce the driver's workload. Second, in this case, this prevents the danger of losing control, which improves the vehicle safety.

The situation can be formulated as

\[ A_{\text{Enable}} = \begin{cases} 1, & P_a = 0, P_b = 0 \text{ and } v_t \geq v_{\text{lim},t} \\ 1, & P_a = 0, P_b > 0 \text{ and } v_t \geq v_{\text{lim},t} \\ 0, & P_a = 0, P_b = 0 \text{ and } v_t < v_{\text{lim},t} \\ 0, & P_a = 0, P_b > 0 \text{ and } v_t < v_{\text{lim},t} \\ 0, & P_a > 0 \end{cases} \] \hspace{1cm} (6)

\[ A_{\text{Enable}} = \begin{cases} 1, & P_a = 0, P_b = 0 \text{ and } v_t \geq v_{\text{lim},t} \\ 1, & P_a = 0, P_b > 0 \text{ and } v_t \geq v_{\text{lim},t} \\ 0, & P_a = 0, P_b = 0 \text{ and } v_t < v_{\text{lim},t} \\ 0, & P_a = 0, P_b > 0 \text{ and } v_t < v_{\text{lim},t} \\ 0, & P_a > 0 \end{cases} \]

\textbf{Deactivating the DSAS}

As shown in Figure 2, mode 1 to mode 3 can be regarded as the transition modes which can connect the DSAS and the energy management strategy. There are three conditions when the DSAS is deactivated: first, the speed is lower than the given value for some time with no pressure on the pedal; second, the accelerator pedal is engaged, which means that \( P_a > 0 \); third, the brake pedal is engaged and the speed has decreased, which means that \( P_b > 0 \) and \( v_t \leq v_{\text{lim},t} \). For the first condition, the speed decreases with the change in the road conditions, and there is no need to assist the downhill driving any more as the vehicle speed is sufficiently safe. For the second condition, the DSAS is deactivated to the energy management strategy when the accelerator pedal is engaged. It can lead to the four main drive modes as normal, which depends on the speed when switching. The second and third conditions are explained together in detail as follows because both
focus on the changes in the driving torque and the braking torque.

**Deactivating from electric motor braking.** If the driver engages the accelerator pedal in mode 4, the electric motor torque increases from a negative braking torque to a positive driving torque as soon as possible. $T_{desire}$ is the demand torque for driving when $P_a > 0$. If there is no extra control, the braking torque increases from $T_{sim}$ to $T_{desire}$ at that moment, and an undesirable longitudinal acceleration occurs, which can cause danger. The accelerator pedal position indicates the driver's intention. If the driver stepped heavily on the accelerator pedal, the torque should increase quickly to match the intention. Thus, the transmitting time from the braking torque to the driving torque depends on the pressure placed on the accelerator pedal. The initial time $t$ is 0 when the driver begins to engage the accelerator pedal in mode 4, $T_M$ is given by

$$T_M = T_{sim} + \frac{T_{desire} - T_{sum}}{\rho(P_a)} t, \quad 0 \leq t \leq \rho(P_a) \quad (8)$$

where $\rho(P_a)$ is the transmitting time of the motor torque from $T_{sum}$ to $T_{desire}$, which decreases as the time increases.

When $P_b > 0$ and $v_i \leq v_{int,b}$, if the desired braking torque from engaging the brake is higher than the motor torque in mode 4, the braking torque should continuously increase with the brake pedal engaged. Without additional control, the braking torque in mode 4 is released at the moment when $P_b > 0$, which can cause an abrupt deceleration. Thus, in our control strategy, the braking torque in mode 4 is maintained when $P_b > 0$. If the desired braking torque is higher than the recent braking torque, it increases at a constant rate until it reaches $T_{m,brk}(P_b)$, according to

$$T_M = \begin{cases} T_{sum} + T_{eng,brk}, \\ T_{sum} + T_{sim,eng} + \frac{T_{desire} - T_{sum} - T_{sim,eng}}{\rho(P_a)} t, \quad \text{clutch state} = 0, \quad 0 \leq t \leq \rho(P_a) \end{cases} \quad (12)$$

and, when $P_b > 0$, the clutch state is 1,

$$T_M = \begin{cases} T_{sum} + T_{sim,eng}, \\ T_{m,brk}(P_b) \end{cases} \quad \text{clutch state} = 0, \quad T_{sum} + T_{sim,eng} \leq T_{m,brk}(P_b) \quad (13)$$

**Deactivating from engine braking.** If the driver steps on the accelerator pedal in mode 6, the clutch is disengaged synchronously to prepare for acceleration. This can cause an abrupt acceleration, which is rather dangerous. This problem is solved by adding a simulation torque $T_{sim,eng}$ to the electric motor, which is equal to $T_{eng,brk}$ of the engine when the clutch is disengaged. The clutch state is 1 when the engine is connected to the powertrain and 0 when it is disconnected from the powertrain. $T_M$ is given by

$$T_M = \begin{cases} 0, \quad \text{clutch state} = 1 \\ T_{sim,eng} + \frac{T_{desire} - T_{sim,eng}}{\rho(P_a)} t, \quad \text{clutch state} = 0, \quad 0 \leq t \leq \rho(P_a) \end{cases} \quad (10)$$

It is the same when $P_b > 0$ and $v_i \leq v_{int,b}$. As the driver steps on the brake pedal, the clutch is disengaged, which can cause a sudden reduction in the braking torque. Thus, the simulation torque $T_{sim,eng}$ is added as the clutch is disengaged. In addition, if $T_{sim,eng} < T_{m,brk}(P_b)$, $T_M$ increases at a constant rate until it reaches $T_{m,brk}(P_b)$, according to

$$T_M = \begin{cases} 0, \quad \text{clutch state} = 1 \\ T_{sim,eng}, \quad \text{clutch state} = 0, \quad T_{sim,eng} \geq T_{m,brk}(P_b) \\ T_{m,brk}(P_b), \quad \text{clutch state} = 0, \quad T_{sim,eng} < T_{m,brk}(P_b) \end{cases} \quad (11)$$

**Mode-shift coordinated control strategy**

The braking modes of the DSAS shown above shift according to the vehicle state. The shift conditions are shown in Figure 2. When the current braking mode shifts to another mode, the braking torque should change continuously by means of the mode-shift coordinated control process. Without this control process, if the braking torque increases or decreases with an abrupt change, it influences the ride comfort and the vehicle safety. Thus, mode-shift coordinated control is quite important in the system.
Electric motor braking to engine braking

When the SOC reaches the threshold value and the engine is off, electric motor braking should exit slowly, which prevents the SOC from overflowing and helps to maintain the speed. Furthermore, engine braking should occur smoothly. As the speed regulation begins, the motor torque is $T_{\text{sum}}$ initially. When the assistance mode changes from mode 4 to mode 6, the motor torque decreases according to

$$T_{\text{total}} = \begin{cases} T_{\text{sum}}, & \text{mode 4} \\ (T_{\text{sum}} - T_{\text{sim,eng}})\theta(t) + T_{\text{eng,b}}, & \text{mode 4} \rightarrow 6 \\ T_{\text{eng,b}}, & \text{mode 6} \end{cases}$$

(14)

where $\theta(t)$ is a function of time, which decreases more quickly as the time increases from a value of 1 to 0 in approximately 5 s; this time is sufficiently long for the vehicle state to change smoothly.

Electric motor braking to electric motor and engine coordinated braking

When the motor torque is not able to maintain the speed within a set of values, the engine braking torque needs to be applied to increase the braking torque. The coordinated braking mode works over a very steep long slope, where the motor torque alone cannot control the speed. When engine braking is added, the braking torque $T_{\text{eng,b}}$ also contributes. To cause the braking torque to change continuously, the mode-shift process is used to control the torque, according to

$$T_{\text{total}} = \begin{cases} T_{\text{sum}} + T_{\text{eng,b}}, & \text{mode 5} \\ T_{\text{sum}}\theta(t) + T_{\text{eng,b}}, & \text{mode 5} \rightarrow 6 \\ T_{\text{eng,b}}, & \text{mode 6} \end{cases}$$

(16)

where $\theta(t)$ is the function as described above for equation (14), which decreases to zero during the transient process. If the slope is so small that the engine braking torque can hold the speed constant, it remains in the engine braking mode. Otherwise, it can cause the speed to increase or return to the coordinated mode, which is described in the following section.

Engine braking to electric motor and engine coordinated braking

If the SOC is still low when the battery can be charged and the speed has increased rapidly, then the electric motor braking is restarted to provide the torque required to maintain a constant speed. Similarly, the motor torque is added according to a curve given by

$$T_{\text{total}} = \begin{cases} T_{\text{eng,b}}, & \text{mode 6} \\ T_{\text{sum}}\xi(t) + T_{\text{eng,b}}, & \text{mode 6} \rightarrow 5 \\ T_{\text{sum}} + T_{\text{eng,b}}, & \text{mode 5} \end{cases}$$

(17)

where $\xi(t)$ represents an ascending curve about the motor torque, with a range from 0 to 1. The maximum value of $\xi(t)$ is 1, which means that the transient process ends.

Actual results from the road experiments

Based on the research object in the second section, we developed an energy management control strategy on an experimental HEB which is shown in Figure 4. The main parameters and the component sizes of the HEB are listed in Table 3. The DSAS that we developed can be added to this HEB. A MicroAutoBox was used to realize the control strategies of our DSAS. A CANcase was used to record the test data for subsequent analysis.

We chose two actual roads (road 1 and road 2) with grades ranging from 0% to 10%, with an average grade...
of approximately 8%, and the downhill road lengths were approximately 3.9 km and 4.5 km for road 1 and road 2 respectively. Because of differences in driving habits, more than 10 drivers took part in the tests and drove normally throughout the process to offer feedback and to verify the control strategy on downhill roads.

The results show the conditions of activating or deactivating the DSAS related to the driver’s operation and the road conditions and according to each driver’s normal driving intentions. Each braking mode of the DSAS was adequately demonstrated during the downhill driving tests. The transient process when the braking modes shifted was also performed to show the control effect. Finally, we used the same experimental conditions of downhill driving with the DSAS and without the DSAS. The average fuel economies and the operation of the drivers were compared to show the advantages of our DSAS.

**DSAS activation and deactivation results**

**Activation and deactivation with the brake pedal applied.** Figure 5 shows the process when the brake pedal was applied. $\Delta V > 0$ indicates that $v_f > v_{inl}$, where $v_f$ is the speed of the vehicle, $v_{inl}$ is the initial speed of the vehicle, and $\Delta V$ is the difference in speed. The permanent-magnet motor torque refers to the rear motor torque. The assistance mode was mode 4, and the speed was kept stable. The brake pedal had three levels proportional to the opening position of the pedal. At 2080.5 s, the driver stepped slightly on the brake pedal. In the previous control strategy, if the DSAS is deactivated, then this caused the speed to increase. However, as proposed above, when the speed increased with the brake pedal applied, the electric motor braking mode still prevented the speed from losing control, which ensured the safety of the vehicle. At 2083 s and 2086 s, even though the braking level reached 2, it was still in the DSAS mode as $\Delta V$ was positive. At 2086.8 s, when $v_f < v_{inl}$, the assistance mode was deactivated and only the electric motor provided the braking torque from the brake pedal, without PID control. The motor torque changed continuously, which matched the control strategy in equation (9). At 2087.3 s, when the speed increased again with $\Delta V > 0$, the assistance mode was activated. Throughout the entire process, the motor torque changed smoothly without any saltation. This process also showed a marked advantage when the driver engaged the brake pedal, as it helped the driver to control the vehicle speed and reduced the driver’s workload.

**Operating modes and mode-shift results**

**The electric motor braking mode.** The electric motor braking mode is shown in Figure 7. At 268 s, when the speed was about 62 km/h, the electric motor braking mode

<p>| Table 3. Main vehicle parameters of the HEB. |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td></td>
</tr>
<tr>
<td>Mass of the vehicle (kg)</td>
<td>13,000</td>
</tr>
<tr>
<td>Length of the vehicle (m)</td>
<td>12</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.65</td>
</tr>
<tr>
<td>Frontal area (m²)</td>
<td>8.05</td>
</tr>
<tr>
<td>Engine</td>
<td></td>
</tr>
<tr>
<td>Engine displacement (l)</td>
<td>5.6</td>
</tr>
<tr>
<td>Maximum power (kW)</td>
<td>162</td>
</tr>
<tr>
<td>Maximum drag torque (N m)</td>
<td>802</td>
</tr>
<tr>
<td>Motor</td>
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</tr>
<tr>
<td>Rated power (kW)</td>
<td>120</td>
</tr>
<tr>
<td>Maximum driving torque (N m)</td>
<td>2100</td>
</tr>
<tr>
<td>Maximum braking torque (N m)</td>
<td>-850</td>
</tr>
<tr>
<td>Battery</td>
<td></td>
</tr>
<tr>
<td>Capacity of the battery (A h)</td>
<td>56</td>
</tr>
<tr>
<td>Charge–discharge rate (C)</td>
<td>10</td>
</tr>
<tr>
<td>Nominal voltage (V)</td>
<td>510</td>
</tr>
</tbody>
</table>

| Figure 5. DSAS activation and deactivation results with the brake pedal applied. PM: permanent-magnet motor. |
was activated when the driver released the accelerator pedal and the brake pedal, and the motor provided a braking torque of $T_{\text{sum}}$ according to PID control in equation (2) to maintain a constant speed. The control error was less than 0.5 km/h with a high accuracy, which cannot be felt by the driver or the passengers. The speed was stable, which ensured driving safety during the downhill driving tests.

The shift of the electric motor braking mode to the electric motor and engine coordinated braking mode. As Figure 8 shows, the speed increased as the driver released the accelerator pedal when moving downhill; thus, the DSAS entered mode 4 at 460 s. However, as the motor torque increased, the speed difference $\Delta V$ also increased. When $\Delta V > V_{h}$, the motor torque had extended the maximum limit at 461 s, and the mode shifted to mode 5, namely the electric motor and engine coordinated braking mode. The engine needed to provide a braking torque. Thus, as the mode shifted to mode 5, the speed regulation observed in Figure 3 occurred successfully. This process lasted from 460.8 s to 465.2 s to ensure that the engine connected smoothly without any oscillations. It can be seen that the speed made the transition coherently at 465 s. The motor torque changed automatically through PID control. We can observe that, during the speed regulation process, $\Delta V$ still increased as the braking torque was not sufficient. At 463.5 s, despite the fact that the clutch state is still 1, the braking torque was sufficiently high with the clutch mostly engaged, which caused $\Delta V$ to decrease. The reason is shown in equation (15); the motor torque subtracted the simulation engine torque $T_{\text{sim.eng}}$ at the onset of mode 5, even though the engine braking torque was not completely added during the clutch engagement time. Therefore, the motor braking torque missed a partition of torque $T_{\text{eng.b}}$, which caused the speed to increase. This can be solved by setting the shift condition to a clutch state of 0.

The shift of the electric motor braking mode to the engine braking mode. The engine braking mode is shown in Figure 9. At 1103 s, the DSAS was activated and provided a motor braking torque. At 1120.6 s, the DSAS shifted to the engine braking mode, as the condition
The speed regulation process lasted from 1120.6 s to 1125 s, when the clutch was engaged. It can be seen that $V$ continued to increase because the engine braking torque was too low to maintain a stable speed. Furthermore, the electric motor cannot provide a braking torque because the SOC was too high for charging. This is one of the disadvantages of the engine braking mode because the engine braking torque cannot adjust as the speed increased. However, because the battery had sufficient capacity, the SOC was rarely charged to a high value. Therefore, mode 6 rarely occurred.

**Performances with the DSAS and without the DSAS**

The experimental results showed the advantages of the DSAS. When driving downhill, the system helped the driver to maintain a stable speed. It is effective over a large range of speeds, which ensured driving safety. The activation or deactivation and the mode shift of the DSAS also allowed the braking torque or the driving torque to make the transition continuously to provide comfort for the ride. The control effects performed well in the HEB.

To determine the optimal performance of the DSAS for HEBs, comparison performance tests were conducted. To provide accurate measurements, we completed four rounds of tests with the developed DSAS and without the developed DSAS on two different downhill roads. The statistics are given in Table 4, which shows the average fuel consumptions and the average electric power consumptions on the two roads. Additionally, the curves showing the driver’s operations and the changes in velocity on the same road with the DSAS and without the DSAS are also provided for comparison in Figure 10 and Figure 11 respectively.

Based on the statistical comparison results in Table 4, the average distances of road 1 and road 2 in the two runs are approximately equal. The average fuel consumption of the HEB with the DSAS is 23.5% less than that of the HEB without the DSAS on road 1 and is 19.6% less on road 2. The electric power consumption is negative when the battery is charging and is positive when the battery is discharging. The average electric power consumption is 128% with the DSAS and is 91% less than that without the DSAS on the

<table>
<thead>
<tr>
<th></th>
<th>Road 1 (with the DSAS)</th>
<th>Road 1 (without the DSAS)</th>
<th>Road 2 (with the DSAS)</th>
<th>Road 2 (without the DSAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance (km)</td>
<td>3.8450</td>
<td>3.9211</td>
<td>4.7882</td>
<td>4.6822</td>
</tr>
<tr>
<td>Average fuel consumption (l/km)</td>
<td>0.1769</td>
<td>0.2267</td>
<td>0.1820</td>
<td>0.2316</td>
</tr>
<tr>
<td>Average electric power consumption (kW h/km)</td>
<td>$-0.4193$</td>
<td>$-0.1803$</td>
<td>$-0.3521$</td>
<td>$-0.1888$</td>
</tr>
</tbody>
</table>

**DSAS:** downhill safety assistance system.

![Figure 9. Results for the shift of the electric motor braking mode to the engine braking mode. PM: permanent-magnet motor.](image)

![Figure 10. Performances with the DSAS by driver A. PM: permanent-magnet motor.](image)
two roads, which suggests that the bus with the DSAS can recycle energy nearly twice as much as that without the DSAS when driving downhill.

From Figure 10 and Figure 11, which show the performances with the DSAS and without the DSAS respectively in terms of the velocity change and the operations of driver A on the same road, it can be observed that the velocity with the DSAS was far more stable than that without the DSAS according to the curves of the velocity change, which suggests an improved ride comfort. It can also be seen that the driver operated the pedals much more frequently in the case without the DSAS. Driver A operated the brake pedal for 32 s and the accelerator pedal for 26 s with the DSAS; the corresponding times without the DSAS are 71 s and 38 s.

Figure 12 and Figure 13 show the performances with the DSAS and without the DSAS respectively by driver B on the same road as in Figure 10 and Figure 11. Similarly, the velocity can be kept stable when reducing operations of the pedals with the DSAS. The driver B operated the brake pedal for 20 s and the accelerator pedal for 14 s with the DSAS; the corresponding times without the DSAS are 87 s and 42 s.

From the comparisons of the electric motor torques and the fuel rates of the engine in the two groups above with the DSAS and without the DSAS by driver A and driver B, the results also show that the system with the DSAS can recycle more electric power with less fuel consumed by the engine.

To conclude, the results indicate that the presented DSAS can work efficiently with various habits of the driver, which significantly reduced the driver’s operation of the pedals, thereby decreasing the workload of downhill driving with improved energy efficiency.

Conclusions
In this paper, a dynamic coordinated control strategy of the DSAS for HEVs was developed. A systematic control strategy is established which can be used for practical application. The actual results for the road experiments based on our DSAS were presented to show its advantages. The main conclusions are as follows.

1. In comparison with the performance without the DSAS, clear advantages of the DSAS include reduced fuel consumption and increased
regenerative braking energy. Furthermore, the system can markedly reduce the driver’s workload and stabilize the speed during downhill driving.

2. Considering the driving habits, the established activation and deactivation control strategy of the DSAS is effective in ensuring a gradual change in the speed when the driver’s operation and the road conditions change, which improves the vehicle safety. Additionally, it makes the DSAS more integrated with the energy management strategy.

3. The mode-shift coordinated control strategy allows the modes to make a transition smoothly without any oscillations and ensures that the vehicle state remains stable during the transition process, which ensures the ride comfort through seamless transitions.

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