H-Bridge Motor Drivers Address Automotive Emissions and ADAS Challenges

Tom Zemites, Motor and Gate Driver Segment Manager,
Pramit Nandy, System and Application Engineer

As a leading supplier of integrated circuits (ICs), software and design-in enabling tools for automotive, including those for motor controls, NXP Semiconductors has designed advanced motor drivers to address critical industry issues. This white paper provides background on automotive challenges, focusing on motor control issues and discusses one of NXP's newest comprehensive solutions to solve them.

Introduction

The automotive industry faces tough challenges within the next decade from lower emission standards worldwide, as well as increased fuel economy regulations, including restricted CO_2 emissions. Motor improvements have been involved in solving many of these automotive control issues for decades. For example, eliminating belt-driven loads and hydraulic controls with electric motors, especially for vehicles with stop/start systems where the engine does not operate at idle, has been an ongoing effort for several years. Also, X-by-Wire terminology covers a broad range of applications for motors used in throttle, brake, steer, shift, suspension, park and other by-wire controls. Building on these automotive successes, new emission control systems and advanced driver assistance systems (ADAS) that phase in over the next two to ten years promise to increase the use, growth and regulatory compliance of motors even further.

Table of Contents

Changes Required for Reducing Greenhouse Gas/CO_2 Emissions

Every major automotive producing and consuming region of the world has increasingly stringent requirements for either increased fuel economy or lower emissions.

- In the United States, in addition to tighter regulations for 2025 from second phase 2017-2025 levels, the government is increasing greenhouse gas (GHG) emissions and fuel economy regulations for medium and heavy-duty vehicles.
- In the European Union (EU), 2020-2021 goals further tighten Euro5 and Euro6 levels with a phase-in for 95% of vehicles in 2020 with 100% compliance in 2021.
- For 2020, Japan will require further fuel economy increases from its 2015 levels.
- China 2020 regulations focus on Phase IV fuel consumption reduction over 2015 requirements.

Table 1 shows a comparison summary of today's versus future requirements.

Country or Region	Regulation	2015-2016 Goal	2020-2025 Goal	Reduction	Increase
European Union	CO_2 (in gCO_2/km)	130	94	26.9%	—
Japan	Fuel economy (in km/L)	16.8	20.3		20.8%
India	CO_2 (in gCO_2/km)	130	113	13.1%	—
China	Fuel economy (in km/L)	6.9	5	27.5%	
United States	Fuel economy (in km/L) or	36.2	56.2	—	55.2%
	CO_2 + other GHGs (in gCO_2/km)	225	143	36.4%	—

Table 1. Continued reductions in emissions and/or increase in fuel economy based on regional regulations.
(After: Figure 2 from "The Automotive CO_2 Emissions Challenge: 2020 Regulatory Scenario for Passenger Cars," Arthur D. Little.)

Increased fuel economy and lower emissions from today's levels (especially for changes over 20%) will require innovation as the most cost-effective means of achieving these goals that have been pursued and implemented for five decades. Today, over 120 motors are in a loaded high-end vehicle. The motors address control applications in body electronics, safety, suspension, engine and emissions control systems. Future automotive systems will increasingly rely on these motors to meet more stringent emissions and fuel economy regulations.

Motor Driver Background

Automotive motors are typically either brushed or brushless DC motors depending on the application. Unlike brushless motors that require six power devices to control the three motor phases, a brushed DC motor only needs four power drivers for speed control, motor direction and braking. Figure 1 shows the basics of an H-bridge controlling a brushed motor.

H-Bridge Operation

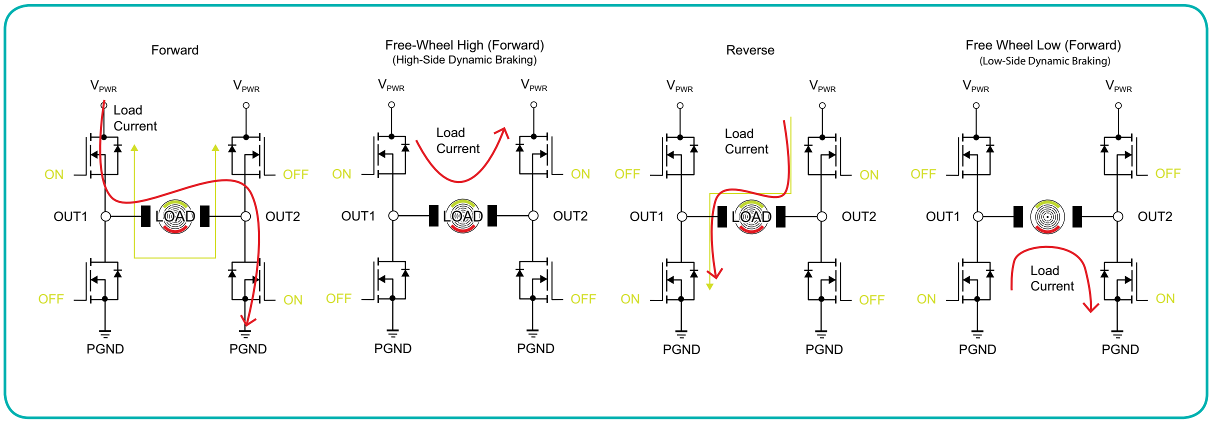

Figure 1. H-bridge Basics

As shown, the two (upper left hand and lower right hand) power MOSFETs control the current in one direction and the amount of current flowing through the motor. Switching on the other two MOSFETs reverses the direction. Turning on either the top two or bottom two MOSFETs provides dynamic braking. Turning on the top and bottom MOSFET on either or both sides results in a direct short. A reverse battery also provides a direct short through the MOSFETs.

In the top legs of the H-bridge, N-channel MOSFETs are most frequently used to avoid the larger area and increased cost of P-channel MOSFETs. In addition to motor driver circuitry, an H-bridge driver IC can provide charge pump circuitry to control the N-channel MOSFETs and other system features, such as system-level diagnostics and closed loop control.

Existing and emerging H-bridge applications focused on emission controls include:

- Throttle control
- Electronic gas recirculation (EGR)
- Fuel injection swirl flaps
- Turbo flaps

In addition to dealing with the reverse battery problem that would provide a direct short from battery positive to ground through the unprotected H-bridge, successful automotive applications for H-bridge controls must also address avalanche of the power MOSFETs, ripple of the supply voltage and switching noise issues from the power transistors.

NXP's H-Bridge Solution

A comprehensive H-bridge driver requires sophisticated analog/mixed-signal technology. Using its established SMARTMOS process, NXP can meet the most demanding system requirements. As shown in Figure 2, SMARTMOS combines the capabilities of leading-edge analog IC, discrete power and MCU and digital technologies.

Figure 2. NXP's SMARTMOS technology provides a unique combination of capabilities for sophisticated ICs

With 25 K logic density, 45 V voltage capability, 45 mΩxmm^2 ($R_{DS(ON)}$*A) @ 45 V and 80 V isolation voltage using trench technology, 0.25 µm SMARTMOS 8 MV technology provides exceptional capability today but that will soon be exceeded in the SMARTMOS 10 HV process. Today's capabilities include:

- Cost-effective high-voltage (110 V) power analog embedded system process platform
- Low $R_{DS(ON)}$*A for thermal efficiency in high-current applications
- High precision for sensor interface integrated with power applications
- Advanced isolation capability (-40 V) and robust system electromagnetic compatibility (EMC) and transient electrostatic discharge (ESD) immunity
- Low-power devices to reduce overall system power consumption
- Wide operating temperature ranging from T_J = -40 to +150°C

Using SMARTMOS technology, the HB2000 and HB20001 are advanced H-bridge motor drivers designed to provide enhanced safety features for high safety integrity, serial peripheral interface (SPI) control for improved flexibility and thermal management for continuous operation.

HB2000 & HB2001 Block Diagram

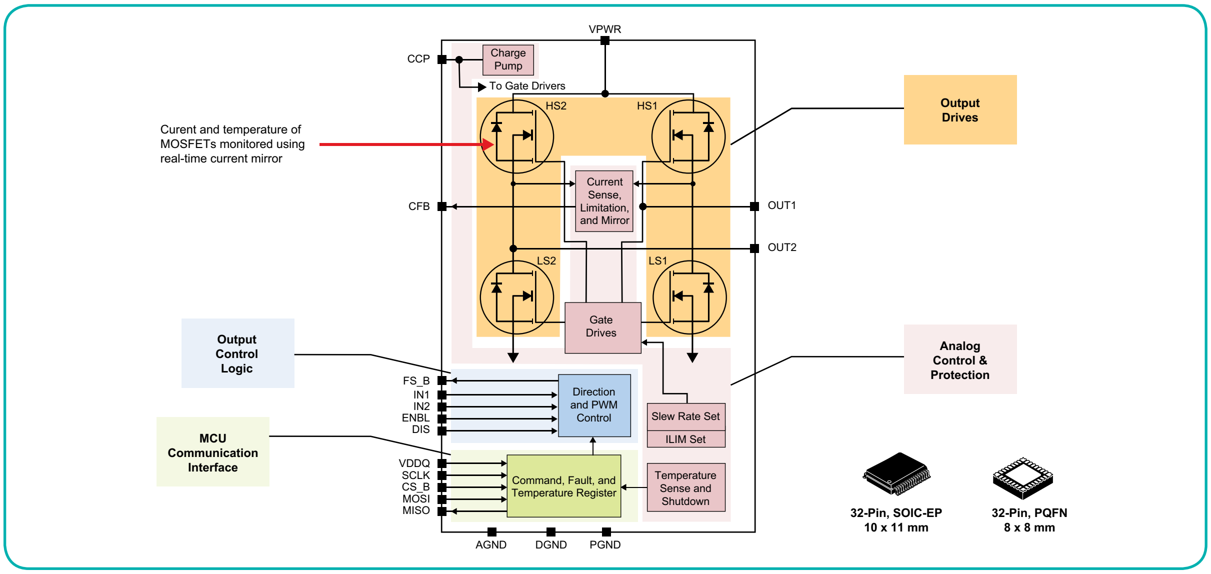

Figure 3. MC33HB2000 & MC33HB2001 architecture and packaging

These motor driver ICs establish product milestones unique in the industry that include:

- First ISO26262 compliant motor driver IC
- Most accurate (<±5%) real-time current feedback
- Lowest $R_{DS(ON)}$ (HB2001)
- Lowest thermal resistance < 1°C/W
- Smallest package
- Widest slew rate selection for continuous operation
- Temperature-dependent current limiting feature

These extremely user-configurable drivers provide a high degree of flexibility for system designers and outstanding thermal management for the harsh automotive environment.

High flexibility is achieved through SPI programmable slew rates and current limits, status flag reporting and SPI diagnostics, configurable as two half bridges, PWM input or SPI control, daisy chainable and real-time current mirror with <±5% tolerance. In addition, since the HB2000 and HB2001 are drop-in replacements, there is no need to change pin-out or software when changing motor drive power requirements.

Eight programmable slew rate settings allow switching the outputs at better than 35 kHz frequency to extremely low PWM frequencies to trade-off between smoother motor control and enhanced EMC performance.

Thermal management includes best-in-class package thermal resistance, lowest $R_{DS(ON)}$ and a temperature-dependent current limit for continuous operation. Four programmable current limit settings allow configuring the part for a wide range of current requirements using simple SPI commands. The ±5% current mirror accuracy allows much greater real-time control and the patented temperature controlled current limit of each device provides much more current for higher motor torque when the motor sticks or binds.

Additional product features/details include:

- Diagnostic reporting via SPI: short to PWR & GRND, overcurrent and overtemperature, overvoltage and undervoltage, open and short load (See Table 2)
- SPI selectable current limits of 5.4/7.0/8.8 and 10.7 A
- SPI selectable slew rates of 0.25, 0.5, 1, 2, 4, 8 and 16 V/µs & by-pass
- H-Bridge and Half-Bridge operation: to drive inductive loads in a full H-bridge and half-bridge configuration
- High-side recirculation: (braking) mode for over voltage protection
- Wide operating range: 5–28 V operation, configurable for operating at 36 V with 40 V transient
- ESD 4 kV at outputs, 36 V proof I/O pins to protect against accidental shorts
- HB2000: <235 mΩ @T_J=150°C
- HB2001: <125 mΩ @T_J=150°C

DIAGNOSTIC REPORTING
OVERTEMPERATURE SHUTDOWN
THERMAL WARNING
OVERCURRENT
OPEN LOAD (in standby mode and in normal full H-bridge operating mode)
SHORT CIRCUIT TO GROUND OUTPUT 1
SHORT CIRCUIT TO GROUND OUTPUT 2
SHORT CIRCUIT TO V_{PWR} OUTPUT 1
SHORT CIRCUIT TO V_{PWR} OUTPUT 2
V_{PWR} OVERVOLTAGE
V_{PWR} UNDERVOLTAGE
CHARGE PUMP UNDERVOLTAGE
SPI FRAMING ERROR

Table 2. List of diagnostics

The ICs have normal operation down to 4 V during crank and up to 32 V after which the overvoltage protection is enabled and up to 36 V when overvoltage protection is disabled.

The 100% pin- and function-compatible HB2000 and HB2001 are initially available in 32-pin 10 x 11 mm SOIC-EP and 32-pin 8 x 8 mm PQFN packages. Table 3 shows the differences.

PACKAGE	PART NUMBER	ON-RESISTANCE (MAX. at T_J = 150°C)	$R\theta_{JC}$ (JUNCTION TO CASE BOTTOM)
PQFN 32	MC33HB2001FN	125 mΩ	<1°C/W
SOIC-EP 32	MC33HB2001EK	125 mΩ	<1°C/W
PQFN 32	MC33HB2000FN	235 mΩ	<1°C/W
SOIC-EP 32	MC33HB2000EK	235 mΩ	<1°C/W

Table 3. Packaging differences for the newest motor driver ICs

Target automotive applications include those in emission systems identified earlier as well as brushed DC motor requirements in body electronics and other vehicle systems as shown in Table 4.

Electronic throttle control	Engine cooling fan
Electric power steering (EPS)	Electric oil pump
Electric water pump	Electric fuel pump
Exhaust gas recirculation (EGR)	Electric parking brake
Turbo flap control	X-by-Wire systems: throttle, brake, steer, shift, suspension, park

Table 4. Austomotive Brushed DC Motor Applications

Body electronics: Windshield wipers, seatbelt retractors, active grill shutters, convertible top, tailgate, seating, mirrors

Addressing Automotive Application Issues

The HB2000 and HB2001 motor driver ICs have several built-in features and a few rather straightforward design tips can simplify their use in automotive applications and address previously identified issues of avalanche breakdown protection, ripple reduction, reverse battery protection, switching noise reduction.

Voltage variations and battery disconnect are among the unique automotive operating conditions that must be addressed for any integrated circuit. If power is interrupted to the power pin (V_{PWR}) input to the HB2000 and HB2001 H-bridge motor driver, the disabled over-voltage protection could cause an unclamped inductive discharge. To prevent electrical overstress of the output drivers, the V_{PWR} should not exceed 40 V during this transient condition.

Avalanche Breakdown and Ripple Reduction

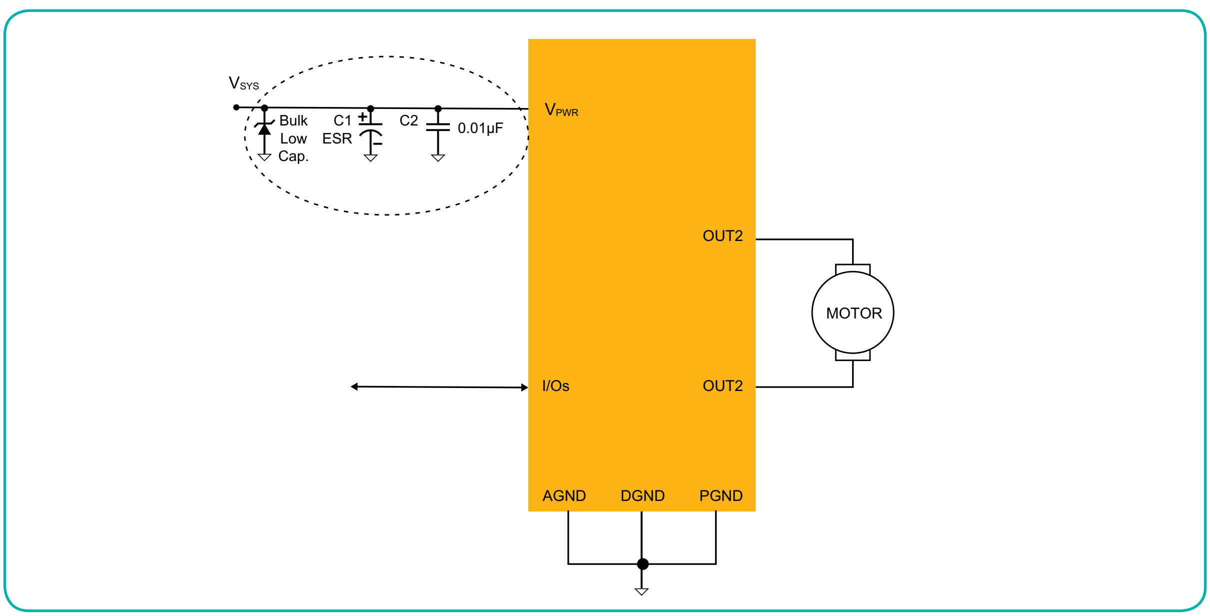

Figure 4. Avalanche breakdown protection implementation and ripple reduction.

As shown in Figure 4, a Zener clamp or metal oxide varistor (MOV), and/or an appropriately valued input capacitor with sufficiently low equivalent series resistance (ESR) can provide this protection. Typically, both a capacitor and an MOV are used, since the capacitor helps reduce the ripple in the system voltage.

The low ESR, high-capacitance capacitor should be selected for the operating frequency to reduce the ripple in the system voltage generated while switching. To do this, the user needs to identify the maximum acceptable ripple allowed in the system voltage line. A small 0.01µF capacitor may be used for filtering high-frequency noise.

Mathematically:

$$\text{ESR Required} = (V_{RIPPLE} / I_{LOAD\_AVG}) - (t_{ON} / C1)$$

t_{ON} = Time for which current flows through the load

C1 = Bulk capacitor capacitance

N-Channel FET for Reverse Battery Protection

Some applications require operation at very low battery voltages (e.g., start-stop applications), and many systems have multiple H-Bridges in parallel, which require high current reverse battery protection with very low voltage drops during the operation. In those situations, an external, reverse-polarity FET may be used instead of the reverse protection diode to reduce the voltage drop from battery to V_{PWR} pins and provide reverse battery protection as shown in Figure 5. The current charge pump (CCP) pin can be used to bias the gate of the N-channel FET, provided its bias current requirement is less than 20 µA. The NPN transistor is used for fast turn-off response of the N-channel FET.

Simplified Application Block Diagram

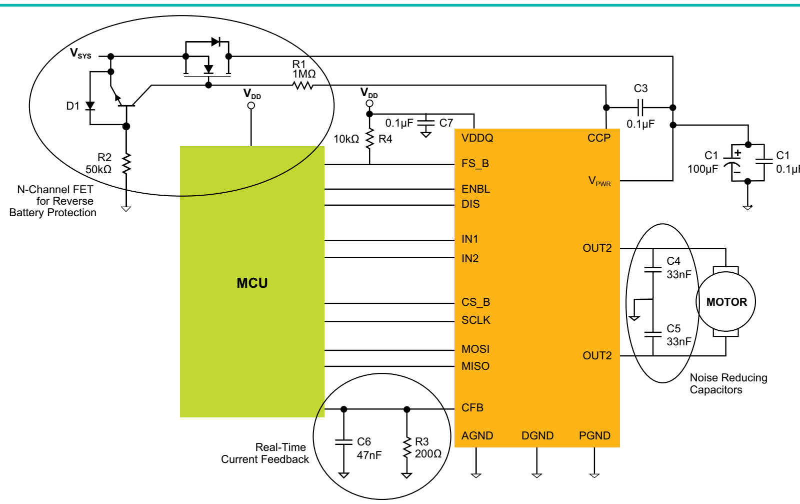

Figure 5. N-Channel FET for reverse battery protection

Capacitor Voltage Diagram

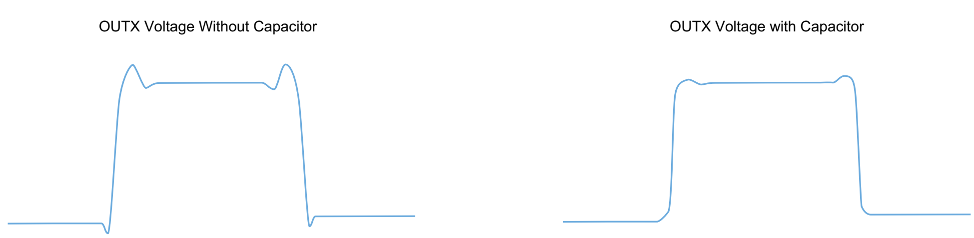

Figure 6. A capacitor on each output helps reduce noise by reducing voltage peaks.

Noise Reducing Capacitors

Using less than a 50 nF capacitor (i.e., 33 nF) on each output as shown in Figure 5 helps reduce the system noise emission by smoothing out the output voltage edges while switching. Figure 6 shows the impact of the capacitor on the output voltage (OUTX).

Real-Time Current Feedback

The current feedback (CFB) pin is a current mirror that provides a current source ratioed to the active high-side MOSFET's current. This feature can be used to provide real-time monitoring of the output current to facilitate closed-loop operation for motor speed/torque control, or for detecting open load conditions. The current from the CFB pin can be converted to voltage using a shunt resistor whose value is based on following parameters:

- Current feedback ratio = 400
- Shunt resistor value = R
- Maximum/Peak current through the high-side power MOSFET/load current for H-bridge = I_{OUTmax}
- Maximum operating voltage for the analog to digital converter (ADC) of MCU = V_{ADCmax}

To prevent any damage to the ADC or CFB pin, the following conditions should be satisfied:

- $V_{ADCmax} \geq (I_{OUTmax} / 400) \times R$
- FB/CFB pin max rating $\geq (I_{OUTmax} / 400) \times R$

Enablement Tools

A sophisticated motor control solution would not be complete without several designer enabling tools. For the HB2000 and HB2001, the tools include an assembled and tested evaluation board/module in anti-static bag, pre-programmed FRDM-KL25Z and a warranty card.

Shown in Figure 8, the EVM for the motor driver ICs has a complete manual and software to simplify system design and reduce time-to-market.

Figure 7. EVM Board for the HB2000 and HB2001

To easily program the many SPI programmable parameters of the HB2000 and HB2001, SPI Generator (SPIGen) software provides a fully customizable software package that is easily accessed through an MCU development platform. As shown in Figure 8, NXP's Freedom (FRDM-KL25Z) platform is an ultra-low-cost development platform for Kinetis L series microcontrollers.

Figure 8. Freedom development platform

Support from a range of NXP and third-party development software with full access to online SDK, tools and reusable code means no downloads, installations or licenses. Linkage of the HB2000 and HB2001 to the FRDM-KL25Z further simplifies the development effort.

Towards More Sophisticated Motor Designs

Based on already stringent requirements compared to a decade or so ago, existing and future regulations for reduced emissions and higher efficiency in automobiles will dictate innovative design changes. Motors promise to be a significant means to provide many innovations and improve automotive control systems. With simpler design and lower cost, brushed DC motors with H-bridge controls will continue to play a significant role in solving control issues in emissions, ADAS and other vehicle systems.

Motor driver ICs that address automotive operating issues and provide significant advances, such as leading-edge accuracy current mirrors and lowest in class on-resistance found in NXP's HB2000 and HB2001, will simplify these innovative design changes. The motor drivers monitor temperature, self-regulate device thermal operation and provide safeguards against device and motor damage.

With enablement tools including evaluation boards and system software, system designers will have greater freedom to pursue and achieve goals that seem beyond reach today. And, just as regulations get tougher and tougher, the product and enablement roadmap for motor driver ICs promises to address these challenges in the future.

Contributors

Tom Zemites
Motor and Gate Driver Segment Manager
Pramit Nandy
System and Application Engineer

How to Reach Us:

Home Page: **www.nxp.com**
Web Support: **www.nxp.com/support**

USA/Europe or Locations Not Listed:
NXP Semiconductors
Technical Information Center, EL516
2100 East Elliot Road
Tempe, Arizona 85284
+1-800-521-6274 or +1-480-768-2130
www.nxp.com/support

Europe, Middle East, and Africa:
NXPHalbleiter Deutschland GmbH
Technical Information Center
Schatzbogen 7
81829 Muenchen, Germany
+44 1296 380 456 (English)
+46 8 52200080 (English)
+49 89 92103 559 (German)
+33 1 69 35 48 48 (French)
www.nxp.com/support

Japan:
NXP Semiconductors
ARCO Tower 15F
1-8-1, Shimo-Meguro, Meguro-ku,
Tokyo 153-0064, Japan
0120 191014 or +81 3 5437 9125
support.japan@nxp.com

Asia/Pacific:
NXP Semiconductors Hong Kong Ltd.
Technical Information Center
2 Dai King Street
Tai Po Industrial Estate
Tai Po, N.T., Hong Kong
+800 2666 8080
support.asia@nxp.com

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