ABSTRACT
From the adoption of driver-assistance cameras to the advancement of fuel efficiency, the intelligence of cars is constantly improving. With these new performance enhancements and their growing power demand, the automotive power management system is responsible for powering and protecting the downstream electronic components during nominal and transient conditions. This application report discusses the unique challenges to designing automotive power supplies.

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1 Introduction

Automotive systems pose unique challenges in order to reliably regulate the car battery voltage to power the sensors and processors which are sensitive to harsh transient conditions. The car battery has a nominal voltage of 12 V to 13.5 V, but during load dump, transients due to a long wire harness or inductive loads, and start-up conditions the battery voltage can vary from –75 V to +50 V. With appropriate input protection the off-battery regulator converts a wide input-voltage range to a constant output in order to protect the downstream components from detrimental input voltage transients.

Always-on components, such as keyless lock systems, demand a low quiescent current from the power module. Consequently, the power supply is required to draw less than 100-µA quiescent current at the module level and to have superior light load efficiency.

An automotive power supply must comply with CISPR 25 conducted- and radiated-emission standards. The CISPR 25 Class 5 limits include stringent requirements for the emission levels in the AM and FM radio bands to ensure the switching regulators do not interfere with the car radio. In order to achieve CISPR 25 compliance, an automotive power supply requires intelligent silicon, package, and system design.

This application report discusses the design challenges that accompany automotive transient conditions and CISPR 25 standards, and potential solutions to enable an automotive-qualified power supply design.

2 Automotive Battery - Transient Conditions

2.1 Start-Up - Soft Start

When a car engine is turned on, the battery output is susceptible to voltage and current spikes. At the front end of an automotive power supply, a DC-DC buck converter is used to regulate an output voltage rail which powers the electronic components throughout the car. These automotive sensors and processors are sensitive to voltage overshoots during start-up; consequently, the off-battery regulator must maintain a constant output despite the battery's transitory behavior.

In order to minimize inrush current and output voltage overshoots during start up, automotive power supplies implement soft start. The LM536XX devices use a reference based soft start, which prevents detrimental transients. A typical start-up waveform of LM53635 is shown in Figure 1.

![Figure 1. LM53635 Soft Start Waveform (Slew Rate = 10,000V/s, 3-Ω Load)](image-url)
2.2 Start-Up - Warm Crank

The battery voltage at start-up varies greatly due to ambient temperature. When the engine cranks at high ambient temperature, a car’s battery voltage drops as low as 6 V. This behavior is referred to as warm crank. The power supply must output a constant voltage rail, typically 3.3 V or 5 V, as the battery voltage drops to 6 V and ramps to a nominal voltage of 12 V to 13.5 V. A wide $V_{IN}$ DC-DC converter can be used to regulate a constant output during start-up conditions depending on the dropout level (the minimum input voltage to maintain regulation). The LM536XX family of wide $V_{IN}$ DC-DC regulators can maintain a constant 5-V output during warm crank conditions as seen in Figure 2.

![Figure 2. LM53635 Warm Crank Response (Green = $V_{IN}$, Yellow = $V_{OUT}$)](image)

2.3 Start-Up - Cold Crank

When the engine cranks at low ambient temperature, a car’s battery voltage can drop to 4.2 V. This behavior is referred to as cold crank. The power supply must output a constant voltage rail, typically 3.3 V, as the battery voltage drops to 4.2 V and ramps to a nominal voltage of 12 V to 13.5 V. A wide $V_{IN}$ DC-DC converter can regulate a constant output during start up conditions depending on the dropout level. The LM536XX family of wide $V_{IN}$ DC-DC regulators can maintain a constant 3.3-V output during cold crank conditions. The cold crank response of the LM53635 is shown in Figure 3 and Figure 4.

![Figure 3. LM53635 Cold Crank Response](image)

![Figure 4. LM53635 Cold Crank Response - Zoomed](image)
2.3.1 Dropout Performance

The dropout level is defined as the difference between the output voltage and the minimum input voltage maintaining regulation. The dropout performance is dependent on the $R_{DS\_ON}$ of the high-side FET, maximum duty cycle, and inductor DCR. The dropout level can be predicted through Equation 1:

$$V_{OUT\_MIN} = (V\_IN \times D_{MAX}) - (R_{DS\_ON} \times I_k) - (R_{DCR} \times I_{L\_RMS})$$

Each version of the LM536XX family has optimized $R_{DS\_ON}$ and consequently improved dropout performance. The high-side FET $R_{DS\_ON}$ specifications of the LM536XX family can be seen in Table 1.

### Table 1. Highside Power Switch On Resistance of LM536XX Family

<table>
<thead>
<tr>
<th></th>
<th>LM53602/3</th>
<th>LM53600/1</th>
<th>LM53625/35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical $R_{DS_ON}$ (mΩ)</td>
<td>95</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>Maximum $R_{DS_ON}$ (mΩ)</td>
<td>200</td>
<td>420</td>
<td>130</td>
</tr>
</tbody>
</table>

The maximum duty cycle of buck converters is typically limited to 98%. This limitation is due to the minimum off-time, or the minimum time the high side FET turns off, and the bootstrap capacitor charges. The LM536XX family operates beyond this time constraint by entering frequency foldback once the duty cycle is maximized. At low input voltages the LM536XX family acts as a constant off-time converter, and the switching frequency decreases. By stretching the frequency the minimum off-time requirements are sustained, and the dropout level is further optimized.

Each generation of the LM536XX has an improved minimum off-time, which widens the input voltage range prior to frequency foldback. The LM536XX minimum off times can be seen in Table 2 and Table 3. Table 2 shows the $t_{\text{Min\_Off}}$ for the 3.3-V output device and the theoretical frequency dropout. Table 3 shows the $t_{\text{Min\_Off}}$ for the 5-V output device and the theoretical frequency dropout.

### Table 2. Minimum Off-time of LM536XX Family (3.3-V Output)

<table>
<thead>
<tr>
<th></th>
<th>LM53602/3</th>
<th>LM53600/1</th>
<th>LM53625/35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical $t_{\text{Min_Off}}$ (ns)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Maximum $r_{\text{Min_Off}}$ (ns)</td>
<td>80</td>
<td>75</td>
<td>60</td>
</tr>
<tr>
<td>1.85-MHz dropout (mV)</td>
<td>336</td>
<td>573</td>
<td>336</td>
</tr>
<tr>
<td></td>
<td>336</td>
<td>532</td>
<td>336</td>
</tr>
</tbody>
</table>

### Table 3. Minimum Off-time of LM536XX Family (5-V Output)

<table>
<thead>
<tr>
<th></th>
<th>LM53602/3</th>
<th>LM53600/1</th>
<th>LM53625/35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical $t_{\text{Min_Off}}$ (ns)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Maximum $r_{\text{Min_Off}}$ (ns)</td>
<td>80</td>
<td>75</td>
<td>60</td>
</tr>
<tr>
<td>1.85-MHz dropout (mV)</td>
<td>509</td>
<td>809</td>
<td>509</td>
</tr>
<tr>
<td></td>
<td>868</td>
<td>806</td>
<td>578</td>
</tr>
</tbody>
</table>
The LM536XX family optimized $R_{DS\_ON}$, $t_{Min\_Off}$, and frequency foldback at low $V_{IN}$ to enable superior dropout behavior, and eliminate a pre-boost stage in most applications. Figure 5 shows the measured dropout behavior of the LM53601 and LM53635 with a fixed 3.3-V output at full load.

![Dropout Behavior Graph](image)

**Figure 5. Measured Dropout Behavior of LM53601 and LM53635 at Full Load (3.3-V Output)**

### 2.4 Automotive Waterfall Test

The waterfall test is a standard automotive test where the input voltage of the DC-DC buck converter starts at the nominal level and is pulsed lower and lower. The waterfall test simulates the battery voltage recovering from deep dropout to its nominal voltage. Figure 6 shows the LM53603 response to the waterfall test. The LM53603 control loop enables a fast response, and consequently, the output voltage responds without overshoot to the recovery of the input voltage. Figure 7 shows a competitor device response to the waterfall test. The competitor device implements a slower control loop response, and consequently, there is a detrimental 500mV overshoot at $V_{OUT}$ due to the pulsing $V_{IN}$.

![Waterfall Test Graphs](image)

**Figure 6. LM53603 Waterfall Test Response (Yellow = $V_{IN}$, Purple = $V_{OUT}$)**  
**Figure 7. Competitor Waterfall Test Response (Yellow = $V_{IN}$, Purple = $V_{OUT}$)**

### 2.5 Battery Life - Quiescent Current Requirements

Automotive systems have a strict quiescent current requirement to preserve battery life. When the car engine is turned off, certain features remain active. In order to power the always on components, the off-battery DC-DC converter is required to have excellent quiescent current and light load efficiency. The quiescent current is required to be less than 100 µA at a module level and less than 30 µA at a front-end DC-DC converter level. The LM536XX family is optimized for quiescent current performance, and the fixed output voltage devices have optimized quiescent current by integrating the feedback resistors and compensation. The LM536XX family of wide $V_{IN}$ regulators has highly efficient light load performance and low quiescent current.
The LM536XX family can operate in Auto mode or FPWM mode. During Auto mode, the device enters PFM mode at light loads and the switching frequency drops in order to maintain high efficiency. Auto mode enables a typical quiescent current of 18 µA.

2.5.1 Efficiency

The efficiency performance must ensure full load regulation at a junction temperature of 150°C and an ambient temperature of 105°C and superior light load efficiency to meet quiescent current requirements. The LM536XX family is designed to have superior light and full load efficiency performance by seamlessly transitioning between PFM and PWM. The efficiency of the LM53635 and LM53603 at 25°C and with nominal input voltage can be seen in Figure 8.

![Figure 8. LM536XX Efficiency vs Output Current](image)

The high efficiency minimizes self-heating due to power losses and the accompanying design concerns. However, it remains important to enhance the thermal performance through an optimized PCB layout.

2.6 Load Dump

Load dump conditions occur when a battery is abruptly disconnected from the alternator or when a load is abruptly disconnected. Figure 9 shows a typical load dump condition: the alternator disconnected from the battery.

![Figure 9. Load Dump Diagram](image)

Consequently, the battery voltage can surge to 65 V to 87 V. Additionally, the ISO7630 standards require bi-directional protection from −75 V to 87 V. Clamping the high energy and high voltage from a load dump becomes very expensive and difficult at the subsystem levels. Consequently, OEMs install a clamping circuit to the alternator, which limits the voltage to a more manageable level for the 30 V to 38 V. In order to protect against the centralized clamped load dump, the LM536XX family does not need any additional protection. The LM536XX family can maintain regulation with a continuous input voltage up to 36 V and a transient voltage of 42 V. This input voltage range is designed to minimize the dissipation across the input protection during input transients.
The automotive market uses synchronous buck converters with a switching frequency greater than 1.8MHz or less than 530kHz in order to avoid interference with the FM and AM radio bands. Since a 2-MHz switching frequency and its harmonics are above the AM radio band, they are valued in the automotive market. However, as the input voltage increases the minimum on time limits the performance. For example, if the $t_{\text{ON Min}}$ is 84 ns, then a 3.3-V output is regulated at 2.1-MHz with a maximum input voltage of 19 V. This can be seen in Equation 2, Equation 3, and Equation 4.

\begin{align*}
D &= \frac{V_{\text{OUT}}}{V_{\text{IN}}} \quad (2) \\
D &= \frac{t_{\text{ON}}}{T_S} \quad (3) \\
V_{\text{IN}} &= \frac{(T_S \times V_{\text{OUT}})}{t_{\text{ON}}} = \frac{(500 \, \text{ns} \times 3.3 \, \text{V})}{84 \, \text{ns}} = 19 \, \text{V} \quad (4)
\end{align*}

Beyond this point, LM536XX implements smooth frequency foldback, and consequently the family is not limited by $t_{\text{ON}}$. Figure 10 shows the smooth frequency foldback behavior for LM53603 compared to a buck converter with a specified constant 2.1-MHz switching frequency, without frequency foldback implemented.

![Figure 10. Switching Frequency vs VIN at 3.5 A for the LM53603](image)

The smooth frequency foldback enables stable regulation at high $V_{\text{IN}}$. Figure 14 shows the performance of a competitor device with a 30-V input and a 1.75-A load. Figure 11 shows the LM53635 output voltage and switch node with a 30-V input and a 1.75-A load. As the competitor device switches at the minimum on-time, the output voltage continues to increase. Once the device reaches the overvoltage level, the high side switch turns off to allow the output capacitor to discharge. Consequently, the minimum on-time limitation causes the large ±100-mV output ripple.

![Figure 11. Competitor Voltage Output Ripple at 30 V.IN](image)  ![Figure 12. LM53635 Voltage Output Ripple at 30 V.IN](image)
3 CISPR 25 Conducted and Radiated Emission Requirements

Conducted and radiated emissions are widely acknowledged to radiate from the switch node of switching power supplies. Consequently, one of the main design challenges of an automotive power supply is passing the CISPR 25 Class 5 conducted and radiated EMI standards, pictured in Figure 13.

![Figure 13. CISPR 25 Class 5 Radiated Emissions Limits](image)

The switch node noise travels through parasitic capacitance to earth ground and the environment, and couples to the input wires. This is the source of common mode noise. A common mode EMI filter can be used at the front end of the power supply in order to attenuate these emissions. The switch node noise also radiates to the board ground plane, and this causes differential conducted noise. A front-end differential EMI filter is typically used to attenuate these emissions. Figure 14 is a visual representation of switch node noise and associated radiations.

![Figure 14. Switch Node Noise Coupling](image)

In automotive power supplies, a regulator’s switching frequency, pinout, PCB layout, and package must be optimized to minimize noise coupling to the board or the environment, and consequently reduce conducted and radiated emissions. These topics are discussed in the following sections.

### 3.1 Switching Frequency

The peak conducted and radiated emissions will be at the regulator switching frequency with additional EMI peaks at its harmonics. The CISPR 25 requirements details the peak and average emissions levels across the AM and FM frequency bands. The LM536XX product family's fundamental switching frequency of 2.1 MHz and its harmonics are above the AM radio band (> 1800 kHz), and consequently, the conducted and radiated emissions are minimized in the strictly regulated AM band. When switching below the AM band (< 530 kHz), additional filtering is required to minimize emissions at the harmonics of the switching frequency.

### 3.2 Pinout Optimization

The key to minimizing conducted and radiated EMI of a switch mode power supply is a good layout. Switching components and high frequency bypass capacitors should be placed as close as possible to each other minimizing the critical path loop area. A quieter switch node enables a reduced $V_{OUT}$ ripple during the switch node $dV/dt$ transitions and improved EMI performance. The LM536XX family’s package and pin-out were designed in order to enable a good layout which minimizes EMI.
The LM53603 device was the first synchronous 2.1-MHz automotive buck converter in the family. In order to optimize the layout, the pinout was designed to enable a low EMI switch mode power supply. The LM53603 has a 16-pin TSSOP package, as pictured in Figure 15. The LM53601 and LM53635 have a FCOL package with wettable flanks, as pictured in Figure 16 and Figure 17. Figure 18 shows a visual representation of the LM53603/02 pinout optimization, and the specific details are discussed in following text.

**Figure 15. LM53603 16-pin TSSOP Package (Top View)**

**Figure 16. LM53601 10-Pin WSON Package (Top View)**

**Figure 17. LM53635 QFN Package (Top View)**

The first key LM53603 pinout enhancement is that the VIN pins are placed close to PGND pins. When the low-side and high-side FETs turn on or off, ripple current flows through the input capacitor. It is critical to minimize the return path for the ripple current in order to minimize EMI. By minimizing the loop area and inductance, the input capacitors are most effective against transient currents. Figure 19 demonstrates the maximum input capacitor path. This layout maximizes the loop inductance, and directly connects the noisy ground plan to the quieter ground plane of the input capacitor loop. A schematic representation of the minimal path for the input capacitors is shown in Figure 20.

**Figure 18. LM53603/02 Pinout Optimization**

Proper supply grouping to allow input caps to be close to the low-side power FET PGND and minimize the loop area and EMC disturbance. N/C is for automotive purpose capacitor spacing of 0.6mm.

CBOOT pin is close to SW pin to minimize the loop area and hence EMC disturbance.

FB node (feedback) is isolated from switching pins and shielded by the AGND pin.
Figure 21 through Figure 24 compare a buck regulator with a minimized CIN loop and a loop area increased by 2.5 times. The analysis is isolated to the effects of loop area by removing the input EMI filter. When the CIN loop area is minimized the output ripple is 64 mVpk-pk, compared to 140 mVpk-pk, and the conducted EMI measurement is decreased by 5 dB. Figure 21 shows the layout with a minimized CIN loop, and Figure 22 shows the layout with a CIN loop increased by 2.5 times. Figure 23 shows the high frequency conducted EMI results for LM53601 with a minimized CIN loop. Figure 24 shows the high frequency conducted EMI results for LM53601 with the CIN loop increased by 2.5 times.

The second critical LM53603 pinout enhancement is that the AGND and FB pins are placed close to each other. The feedback node should be isolated from the switch node and is shielded by AGND. This placement protects noise at the switch node from coupling to the sensitive analog feedback pin.
The third key LM53603 pinout optimization is that the CBOOT and SW pins are placed close to each other. This allows the boot capacitor to be placed directly next to the component minimizing the loop area.

When developing the LM53635, the pinout was further optimized to ease layout constraints and optimize EMI performance. PVIN1, PVIN2, PGND1, and PGND2 pins are placed on either side of the LMS3635 in order to further minimize the loop area. Placing two high-frequency input capacitors on either side of the LM53635 cuts parasitic inductance of the path in half. Consequently, this layout decreases the dv/dt of the input capacitor loop. The optimized layout of the input capacitors is shown in Figure 25.

![Figure 25. High-Frequency Input Capacitors Layout](image)

The second key LM53635 pinout enhancement is that the VCC and BiAS pins are placed close to AGND. Bypass capacitors are placed between these two pins and AGND to minimize noise coupling.

In summary the LM536XX family offers an optimized pinout design to ease layout requirements and optimize the EMI performance of the switching power supply.

### 3.3 Package Optimization

Package lead inductance substantially affects the EMI performance of a regulator by increasing the switch node ringing; the high frequency emissions associated with switch node ringing are extremely difficult to filter out. A wire-bond package, Figure 26, has significant lead inductance compared to a flipped chip on lead (FCOL) package, Figure 27. Automotive hotrod technology eliminates wire bonds by attaching the silicon die directly to the lead frame. Consequently hotrod technology lowers $R_{DS\_ON}$, parasitic lead inductance, and dramatically reduces switch node ringing.

The LM53635 and LM53625 are the first devices in this family to use automotive hotrod technology. The switch node waveforms of a wire bond package and an automotive hotrod package can be seen in Figure 28 and Figure 29. The LM53635 FCOL package switch node shows no ringing, which simplifies the EMI filter design. The increased switch node ringing of wire-bond devices can be challenging to filter out and will most likely require a metal shielding cage to pass CISPR 25 Class 5 limits.

![Figure 26. Standard QFN Package](image)

![Figure 27. FCOL QFN Package](image)
3.4 Spread Spectrum

Spread spectrum is a factory feature in the LM53600/1 and LM53625/35, which reduces conducted EMI by 10 dB in the 30 MHz to 108 MHz frequency band. Above 50 MHz the EMI filter inductor begins self-resonating; spread spectrum significantly attenuates the emissions in the frequency range where the EMI filter is ineffective. Consequently, spread spectrum can eliminate the need for a common mode choke or metal shielding.

Spread spectrum reduces the EMI by dithering the switching frequency by ±4%. A shift register produces a pseudo-random code which is passed to an oscillator. This oscillator provides a pseudo-random current. Consequently, the fundamental frequency’s signal energy is decreased while widening the spectrum.

A 17-bit linear feedback shift register generates pseudo-random codes that vary the switching frequency by ±4% in this case ±84 kHz. This is still above the AM band frequency of 1.8 MHz. The code changes the current ripple depending on the adjustment in the frequency. $I_{\text{ripple}} = (V_{\text{IN}} - V_{\text{OUT}}) \times V_{\text{OUT}} / (f_{\text{SW}} \times V_{\text{IN}} \times L)$, this in turn changes the O/P voltage ripple marginally $\Rightarrow V_{\text{ripple}} = ESRC_{\text{out}} \times I_{\text{ripple}}$.

Figure 30 and Figure 32 show the conducted emissions results of the LM53635 without spread spectrum. Figure 31 and Figure 33 show the conducted emissions results of the LM53635 with spread spectrum. The yellow curve is the peak measurements, and the blue curve is the average measurements. As seen in Figure 30 through Figure 33, the harmonics of the high frequency emissions are greatly reduced by spread spectrum.
4 Summary

The transient conditions of a car battery and the strict CISPR 25 Class 5 limits pose unique power supply design challenges in order to protect the various signal chain components and processors. An off-battery wide $V_{IN}$ DC-DC converter provides a robust solution to regulate a constant output voltage and comply with stringent automotive requirements. Texas Instruments offers the LM536XX synchronous buck converter family with superior dropout, efficiency, transient response, and EMI performance designed specifically to meet the system requirements of automotive off-battery applications.
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