

Designing High-Performance, Low-EMI Automotive Power Supplies

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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.

Contents

1	Introduction	3
2	Automotive Battery - Transient Conditions	3
3	CISPR 25 Conducted and Radiated Emission Requirements	9
4	Summary	14

List of Figures

1	LM53635 Soft Start Waveform (Slew Rate = 10,000V/s, 3-Ω Load)	3
2	LM53635 Warm Crank Response (Green = V_{IN} , Yellow = V_{OUT})	4
3	LM53635 Cold Crank Response	4
4	LM53635 Cold Crank Response - Zoomed	4
5	Measured Dropout Behavior of LM53601 and LM53635 at Full Load (3.3-V Output)	6
6	LM53603 Waterfall Test Response (Yellow = V_{IN} , Purple = V_{OUT})	6
7	Competitor Waterfall Test Response (Yellow = V_{IN} , Purple = V_{OUT})	6
8	LM536XX Efficiency vs Output Current	7
9	Load Dump Diagram	7
10	Switching Frequency vs V_{IN} at 3.5 A for the LM53603	8
11	Competitor Voltage Output Ripple at 30 V_{IN}	8
12	LM53635 Voltage Output Ripple at 30 V_{IN}	8
13	CISPR 25 Class 5 Radiated Emissions Limits	9
14	Switch Node Noise Coupling	9
15	LM53603 16-pin TSSOP Package (Top View)	10
16	LM53601 10-Pin WSON Package (Top View)	10
17	LM53635 QFN Package (Top View)	10
18	LM53603/02 Pinout Optimization	10
19	Schematic Representation of Maximum Critical Path for Input Capacitors	10
20	Schematic Representation of Minimal Critical Path for Input Capacitors	10
21	Layout with C_{IN} Loop Area Minimized	11
22	Layout with C_{IN} Loop Area Increased by 2.5 Times	11
23	Conducted EMI Results for LM53601 with C_{IN} Loop Minimized	11
24	Conducted EMI Results for LM53601 with C_{IN} Loop Increased by 2.5 Times	11
25	High-Frequency Input Capacitors Layout	12

26	Standard QFN Package	12
27	FCOL QFN Package.....	12
28	Wirebond Device Switch Node Signal (13.5 V _{IN} ; 3.3 V _{OUT} ; 3-Ω Load).....	13
29	LM536X5 Switch Node Signal (13.5 V _{IN} ; 3.3 V _{OUT} ; 3-Ω Load).....	13
30	Conducted Emissions 150 kHz to 30 MHz - Spread Spectrum Disabled.....	13
31	Conducted Emissions 150 kHz to 30 MHz - Spread Spectrum Enabled	13
32	Conducted Emissions 30 MHz to 108 MHz - Spread Spectrum Disabled.....	14
33	Conducted Emissions 30 MHz to 108 MHz - Spread Spectrum Enabled	14

List of Tables

1	Highside Power Switch On Resistance of LM536XX Family	5
2	Minimum Off-time of LM536XX Family (3.3-V Output)	5
3	Minimum Off-time of LM536XX Family (5-V Output).....	5

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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 $+50\text{ V}$. 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 $100\text{-}\mu\text{A}$ 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.

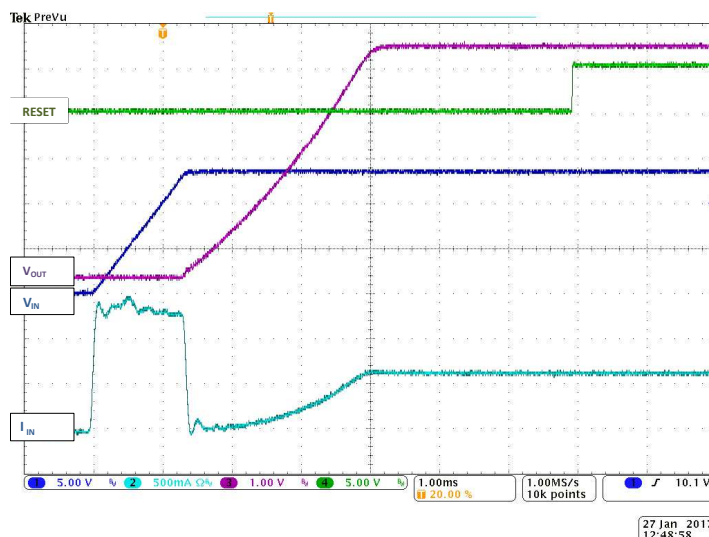


Figure 1. LM53635 Soft Start Waveform (Slew Rate = $10,000\text{V/s}$, $3\text{-}\Omega$ Load)

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 up 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.

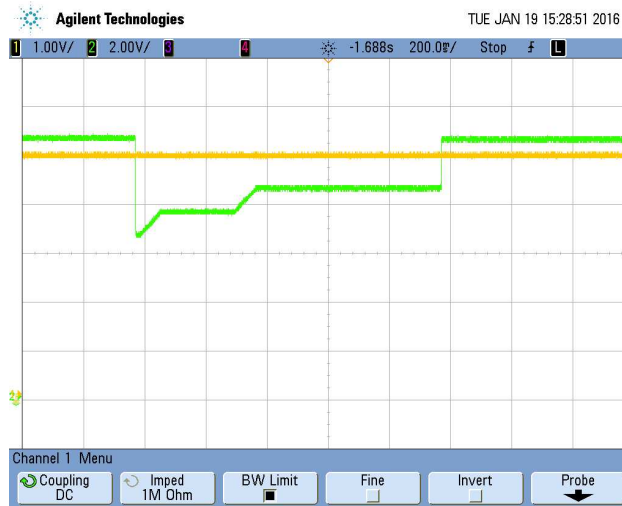


Figure 2. LM53635 Warm Crank Response (Green = V_{IN} , Yellow = V_{OUT})

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 up 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.

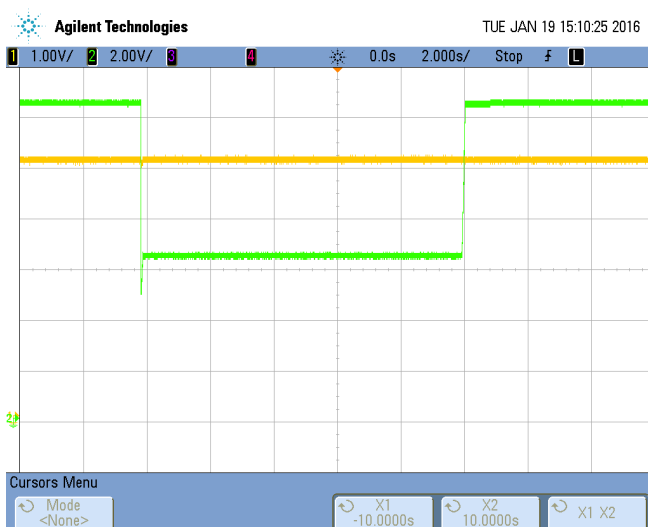


Figure 3. LM53635 Cold Crank Response

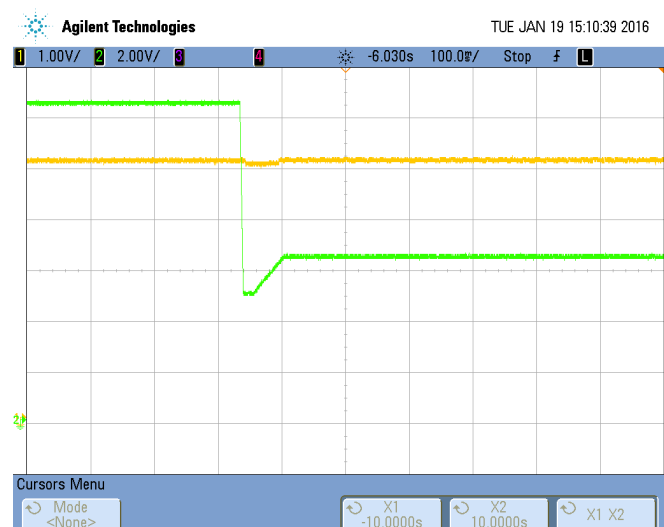


Figure 4. LM53635 Cold Crank Response - Zoomed

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:

$$V_{OUT_Min} = (V_{IN} \times D_{MAX}) - (R_{DS_ON} \times I_{IN}) - (R_{DCR} \times I_{L_RMS}) \quad (1)$$

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

LM53602/3		LM53600/1		LM53625/35		
	Typical	Maximum	Typical	Maximum	Typical	Maximum
R_{DS_ON} (mΩ)	95	200	200	420	60	130

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_{Min_Off} for the 3.3-V output device and the theoretical frequency dropout. Table 3 shows the t_{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)

LM53602/3		LM53600/1		LM53625/35		
	Typical	Maximum	Typical	Maximum	Typical	Maximum
Minimum Off-time (ns)	50	80	50	75	50	60
1.85-MHz dropout (mV)	336	573	336	532	336	381

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

LM53602/3		LM53600/1		LM53625/35		
	Typical	Maximum	Typical	Maximum	Typical	Maximum
Minimum Off-time (ns)	50	80	50	75	50	60
1.85-MHz dropout (mV)	509	868	509	806	509	578

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.

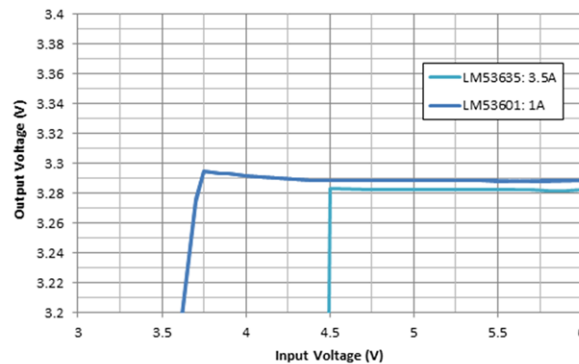


Figure 5. Measured Dropout Behavior of LM53601 and LM53635 at Full Load (3.3-V Output)

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} .

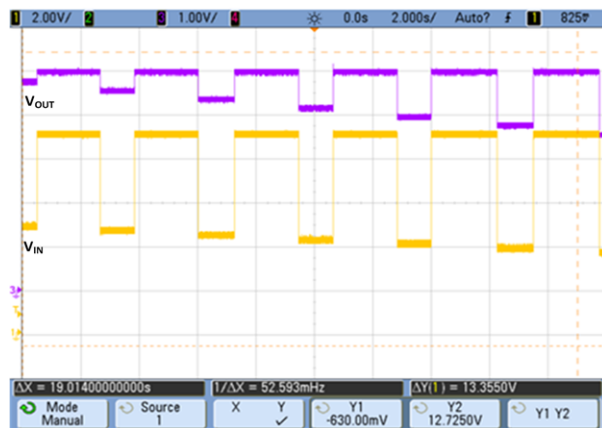


Figure 6. LM53603 Waterfall Test Response (Yellow = V_{IN} , Purple = V_{OUT})

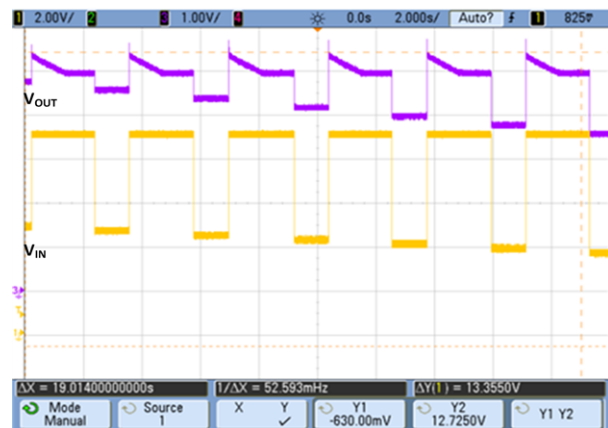


Figure 7. Competitor Waterfall Test Response (Yellow = V_{IN} , Purple = V_{OUT})

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 μ A.

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.

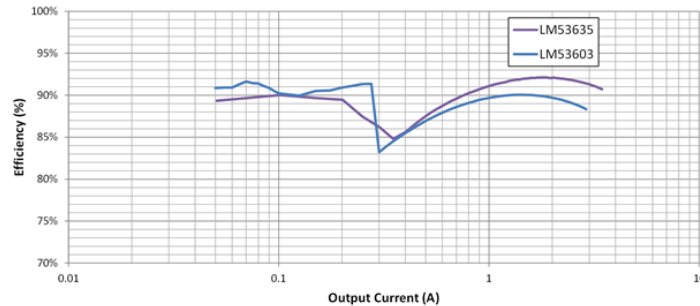


Figure 8. LM536XX Efficiency vs Output Current

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.

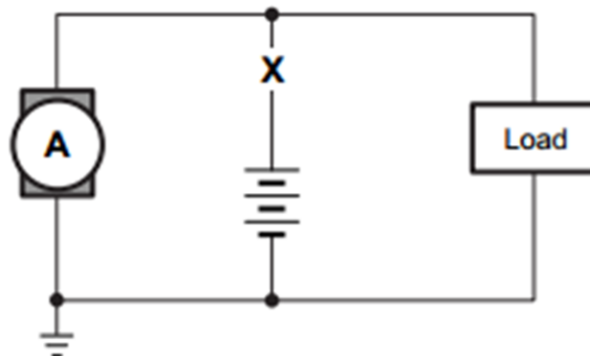


Figure 9. Load Dump Diagram

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_{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.

$$D = V_{OUT} / V_{IN} \tag{2}$$

$$D = t_{ON} / T_S \tag{3}$$

$$V_{IN} = (T_S \times V_{OUT}) / t_{ON} = (500 \text{ ns} \times 3.3 \text{ V}) / 84 \text{ ns} = 19 \text{ V} \tag{4}$$

Beyond this point, LM536XX implements smooth frequency foldback, and consequently the family is not limited by t_{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.

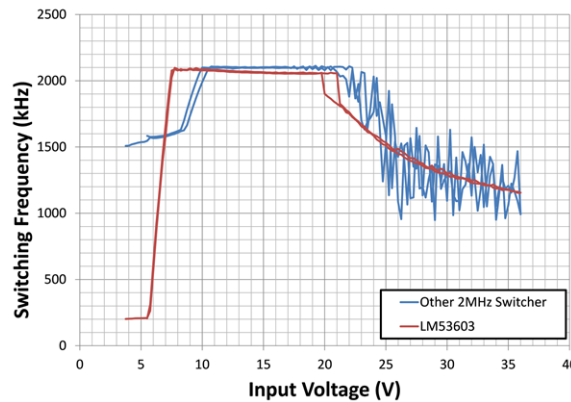


Figure 10. Switching Frequency vs VIN at 3.5 A for the LM53603

The smooth frequency foldback enables stable regulation at high V_{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.

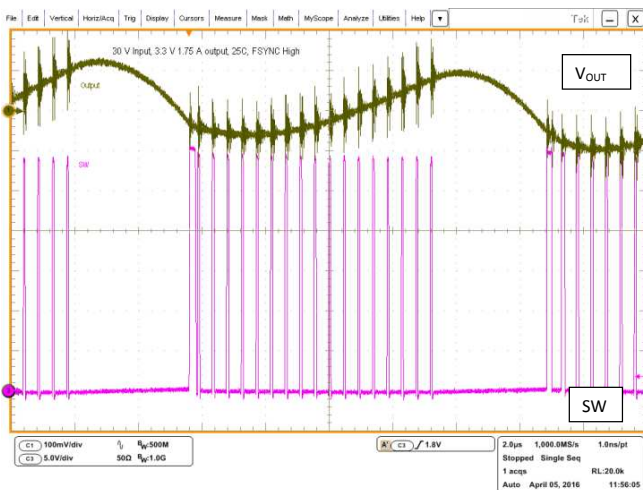


Figure 11. Competitor Voltage Output Ripple at 30 V_{IN}

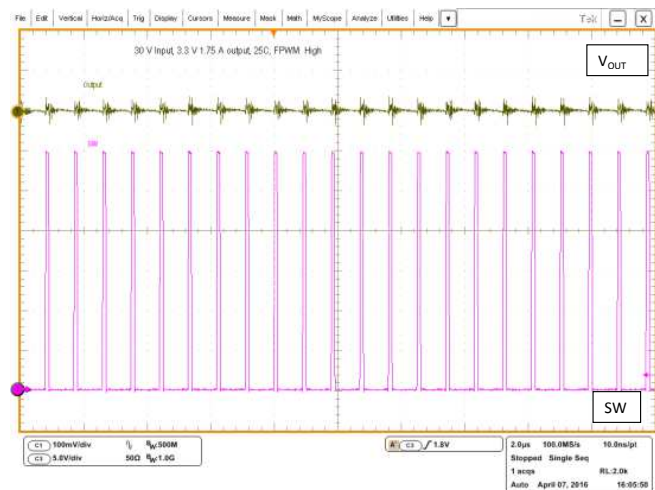


Figure 12. LM53635 Voltage Output Ripple at 30 V_{IN}

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.

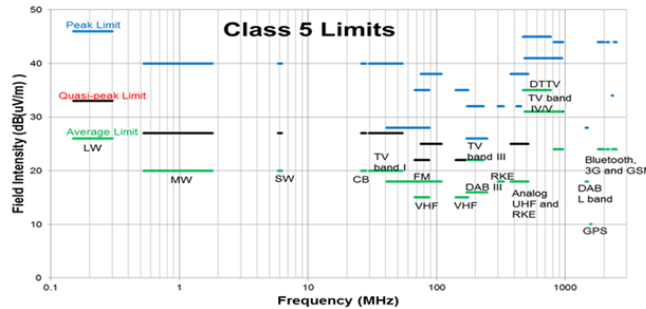


Figure 13. CISPR 25 Class 5 Radiated Emissions Limits

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.

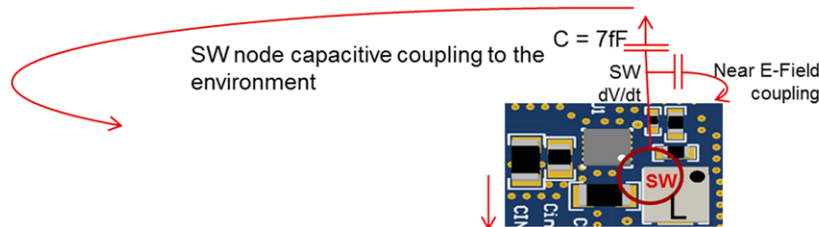


Figure 14. Switch Node Noise Coupling

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.

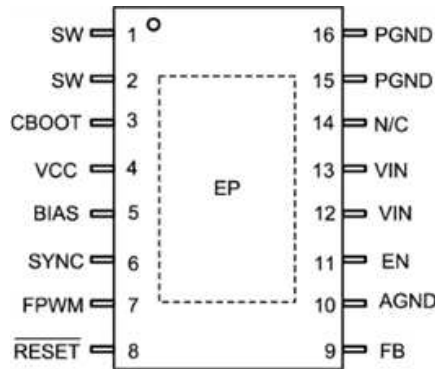


Figure 15. LM53603 16-pin TSSOP Package (Top View)

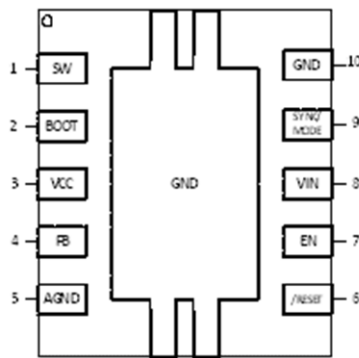


Figure 16. LM53601 10-Pin WSON Package (Top View)

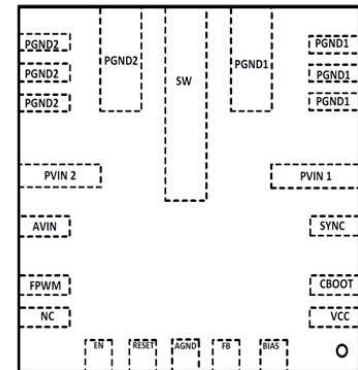


Figure 17. LM53635 QFN Package (Top View)

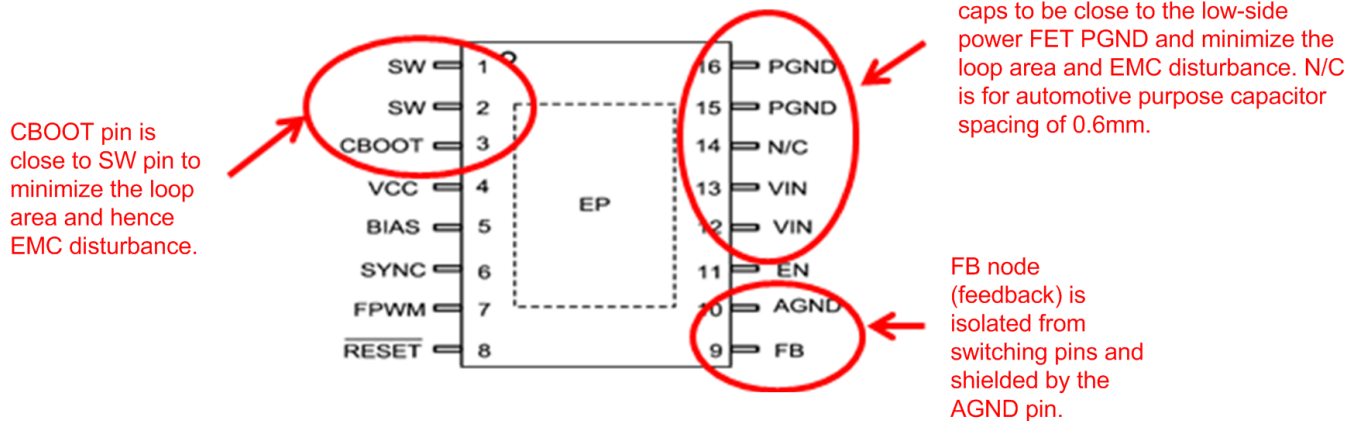


Figure 18. LM53603/02 Pinout Optimization

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.

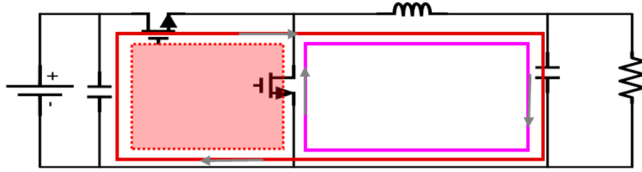


Figure 19. Schematic Representation of Maximum Critical Path for Input Capacitors

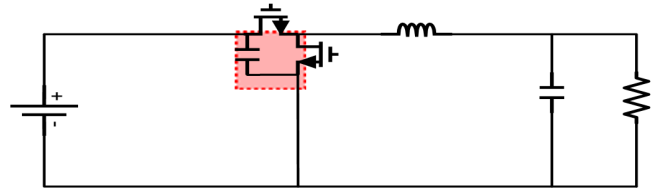


Figure 20. Schematic Representation of Minimal Critical Path for Input Capacitors

Figure 21 through Figure 24 compare a buck regulator with a minimized C_{IN} 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 C_{IN} 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 C_{IN} loop, and Figure 22 shows the layout with a C_{IN} loop increased by 2.5 times. Figure 23 shows the high frequency conducted EMI results for LM53601 with a minimized C_{IN} loop. Figure 24 shows the high frequency conducted EMI results for LM53601 with the C_{IN} loop increased by 2.5 times.

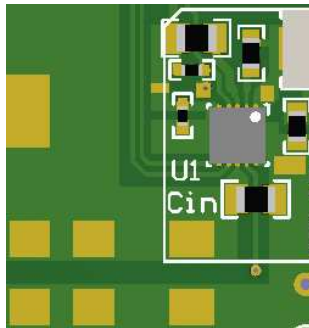


Figure 21. Layout with C_{IN} Loop Area Minimized

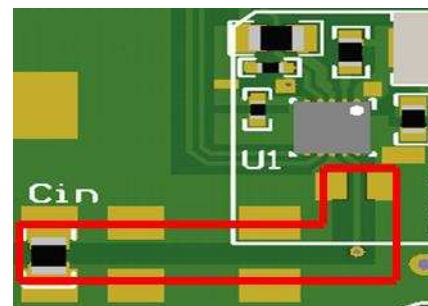


Figure 22. Layout with C_{IN} Loop Area Increased by 2.5 Times

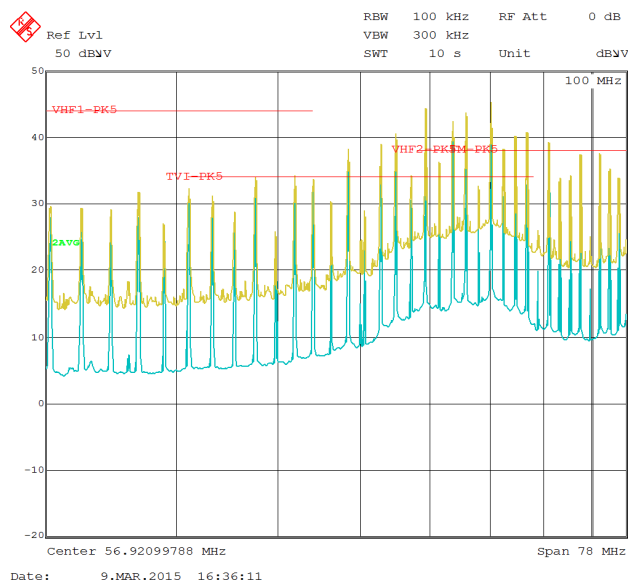


Figure 23. Conducted EMI Results for LM53601 with C_{IN} Loop Minimized

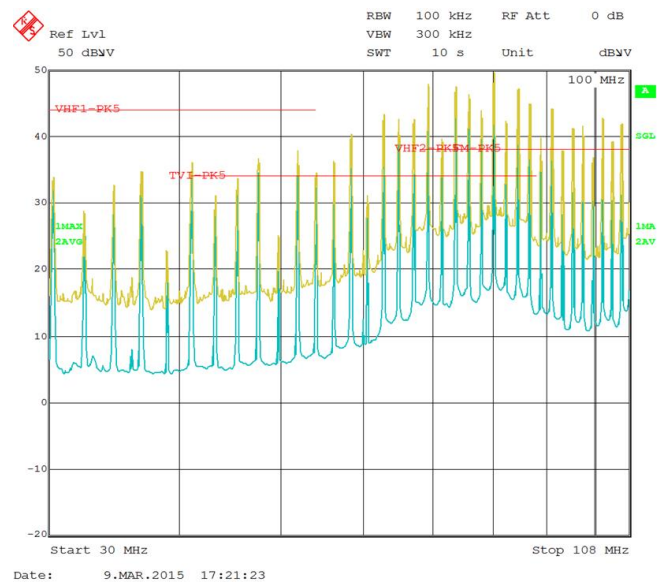


Figure 24. Conducted EMI Results for LM53601 with C_{IN} Loop Increased by 2.5 Times

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](#).

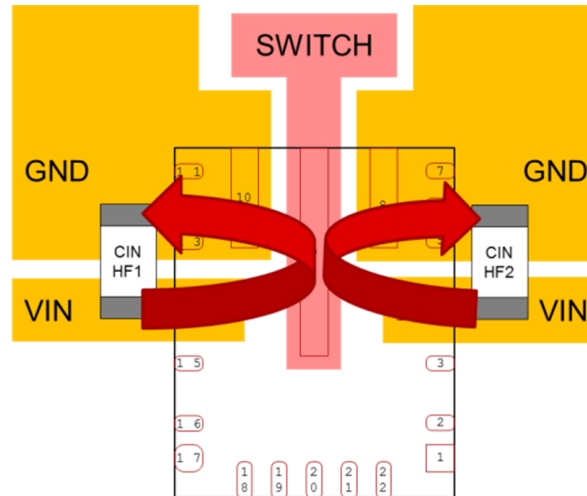


Figure 25. High-Frequency Input Capacitors Layout

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.

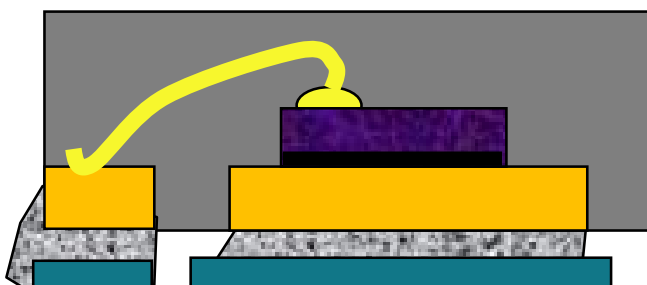


Figure 26. Standard QFN Package

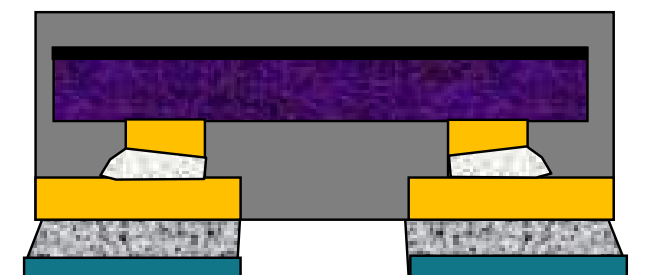


Figure 27. FCOL QFN Package

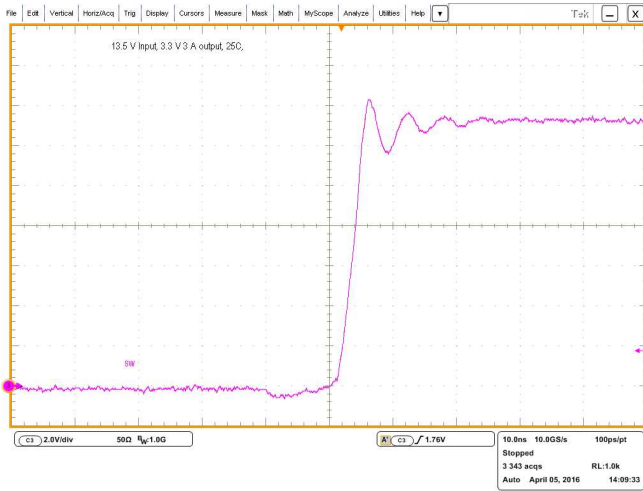


Figure 28. Wirebond Device Switch Node Signal (13.5 V_{IN}; 3.3 V_{OUT}; 3-Ω Load)

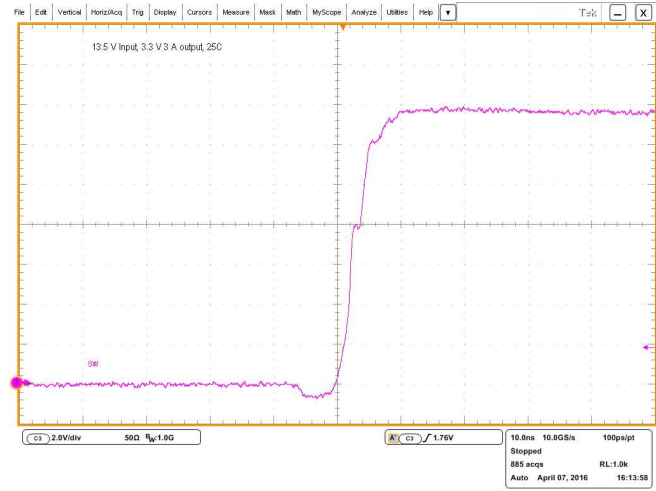


Figure 29. LM536X5 Switch Node Signal (13.5 V_{IN}; 3.3 V_{OUT}; 3-Ω Load)

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 $\pm 4\%$. 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 $\pm 4\%$ 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 $\Rightarrow V_{\text{ripple}} = \text{ESRCout} \times I_{\text{ripple}}$.

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.

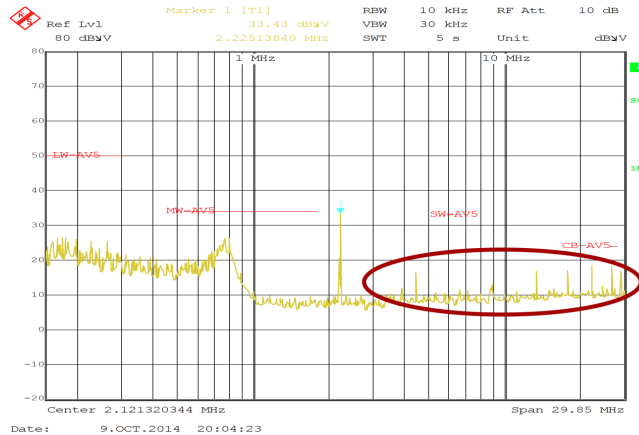


Figure 30. Conducted Emissions 150 kHz to 30 MHz - Spread Spectrum Disabled

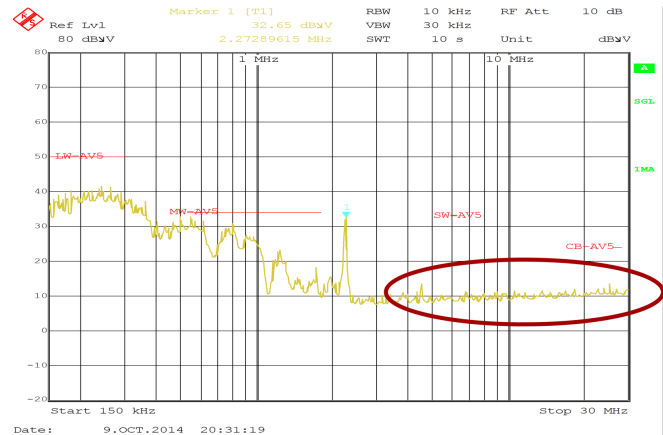


Figure 31. Conducted Emissions 150 kHz to 30 MHz - Spread Spectrum Enabled

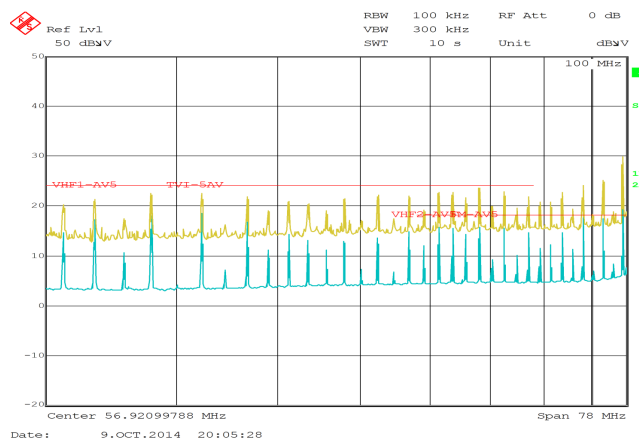


Figure 32. Conducted Emissions 30 MHz to 108 MHz - Spread Spectrum Disabled

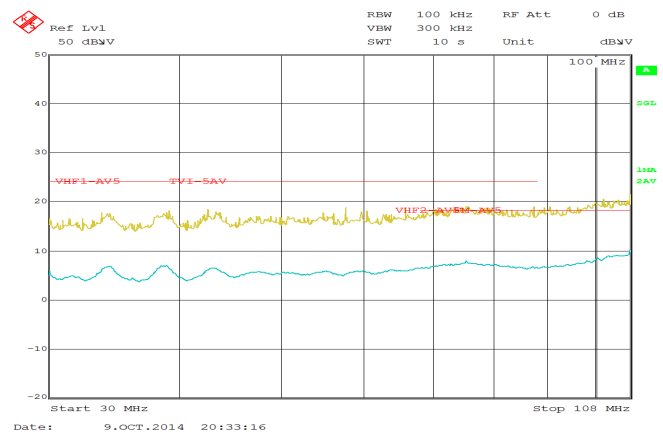


Figure 33. Conducted Emissions 30 MHz to 108 MHz - Spread Spectrum Enabled

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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