TI Designs
Automotive, Four-Channel, Class D Amplifier Reference Design for Head Unit

Design Overview

This design provides a Class D-based amplifier solution that allows it to be evaluated in the form factor of a typical Class AB amplifier. The design is optimized to mitigate thermals associated with audio amplifiers and to minimize switching noises associated with Class D amplifiers. This design consists of two circuit boards. The first board highlights the audio amplifier module. The second board highlights circuitry to incorporate the amplifier module into a base board. The pair of boards allows stand-alone performance testing of the design.

Design Resources

TIDA-00573	Tool Folder Containing Design Files
TAS5404-Q1	Product Folder
TL760M33-Q1	Product Folder

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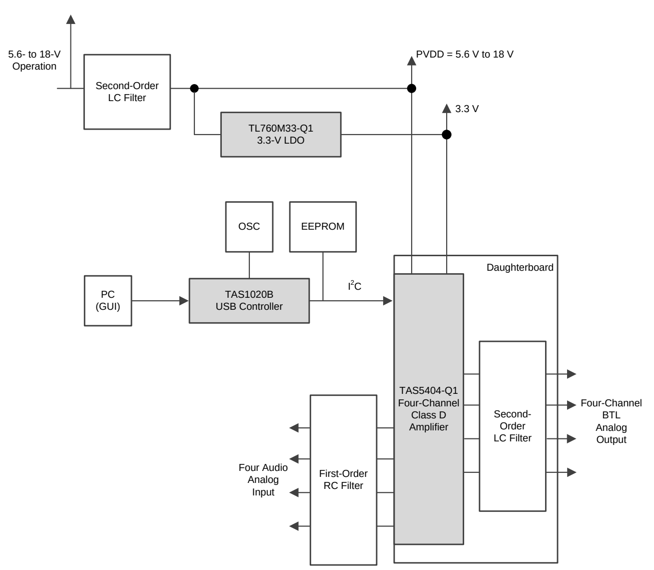
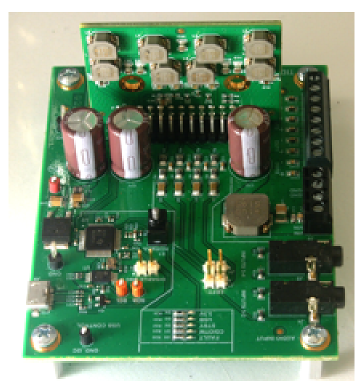
Design Features

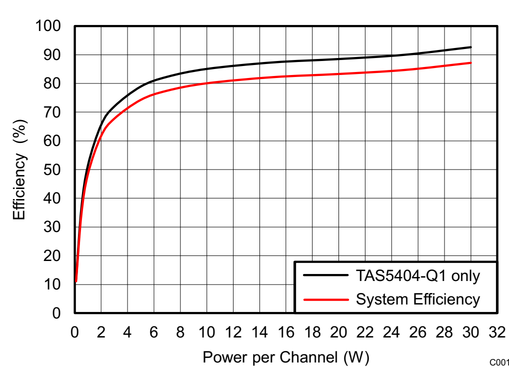
- Withstands Load-Dump Conditions
- Size and Space Optimized Design
- CISPR-25 Tested EMI
- Withstands Start/Stop Operation Down to 5.6 V

Featured Applications

- Automotive Color Media or Display Audio
- Automotive Mid- and Low-Head Units
- Automotive Seat Vibration
- Audio Amplifier Modules







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1 System Description

This system has been designed to be a form, fit, and functional evaluation of the typical configuration of Class AB amplifiers in an integrated amplifier head unit. To accommodate this purpose, the following design points have been considered:

- Support of the vertical profile of the audio amplifier to allow it to use the metal housing of an existing head unit as a heat sink
- Off-battery voltage support including line noise filters that receive power from the reverse battery protection circuit incorporated off of the base board
- Speaker drive filter integration to eliminate noise coupling into the AM radio band

To ease the design of this module into a head unit base board, a companion board has been included. This board highlights the decoupling capacitors, analog input noise filters, and the appropriate layout considerations for incorporating the module into the design (see Figure 1).

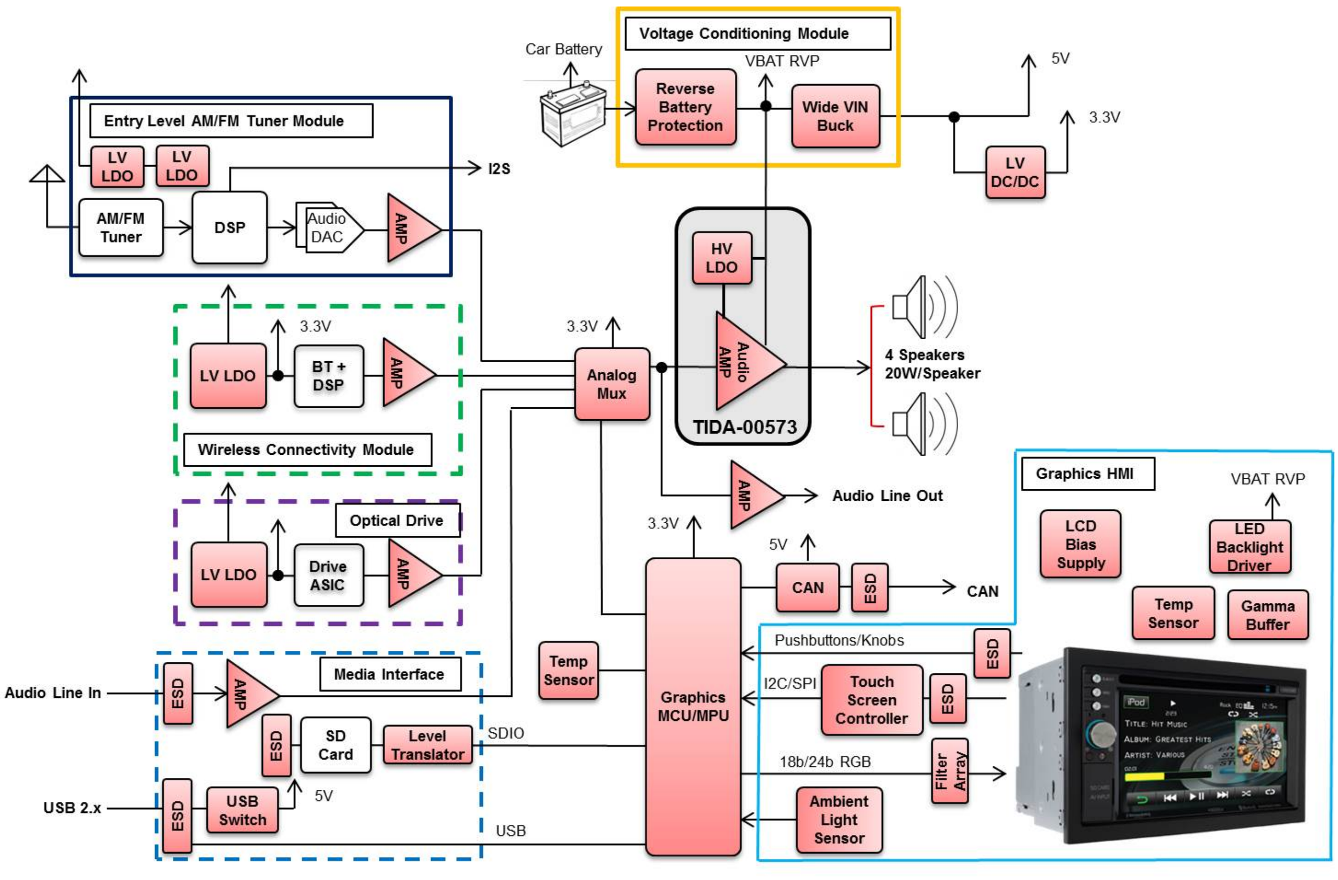

Figure 1. Automotive Head Unit With Integrated Display Example Highlighting TIDA-00573

2 Key System Specifications

Table 1. Audio Module System Specifications

PARAMETER		COMMENTS	MIN	TYP	MAX	UNIT
System input						
V_{IN}	Operational input voltage	Battery voltage range audio amp is functional (DC)	5.6	14	18	V
V_{MAX}	Maximum input Voltage	Maximum battery voltage on the module without device damage	–0.3		30	V
I_{STDBY}	Input current	All four channels in MUTE mode		170	220	mA
Audio input						
V_{AIN}	Maximum audio input voltage			19		V_{RMS}
V_{LOGIC}	Input voltage range for IO pins	I^2C lines, MUTE, standby	–0.3		6	V
Audio performance (V_{IN} = 14.4 V)						
P_{OUT}	Output power per channel	4-Ω speaker load driven		22		W
P_{EFF}	Power efficiency	4-Ω speaker load driven		90		%
PSRR	Power supply rejection	1-V_{RMS} ripple on 14.4-V supply		75		dB
THD	Total harmonic distortion	1-W output		0.02		%
Thermals						
T_J	Maximum operating junction temperature	TAS5404-Q1 junction temperature	–55		150	°C

3 Block Diagram

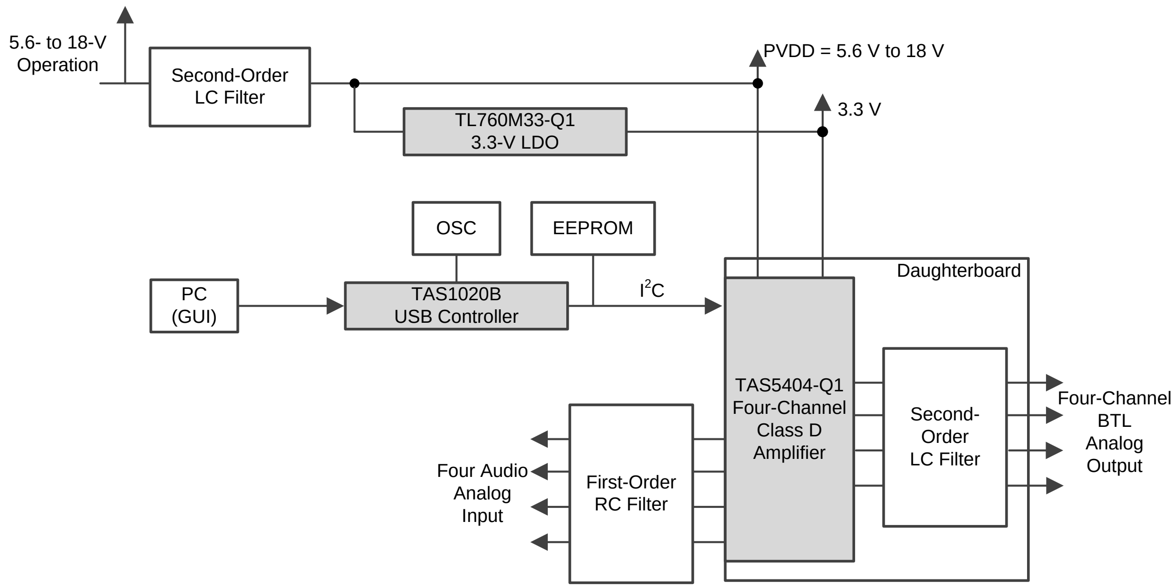

Figure 2. Automotive, Four-Channel, Class D Amplifier for Head Unit

3.1 Highlighted Products

The TIDA-00573 design uses the following TI products:

- TAS5404-Q1: This device is a four-channel digital audio amplifier with an input voltage range from 5.6 V to 18 V (50-V load dump), which enables it to work directly from an automotive battery.
- TL760M33-Q1: This device is a low-dropout regulator (LDO) with several fixed-voltage options with the capability of sourcing 500 mA of current. This device has been added to the design to showcase the interaction of the Class D amplifiers with a head unit; therefore, this document does not describe it in full detail.
- TAS1020B: This device is a universal serial bus (USB) peripheral interface device for isochronous data streaming. In this design, the TAS1020B connects the graphical user interface (GUI) to the board to set the I^2C address, data, and diagnostics for the TAS5404-Q1. This device performs functions normally performed by the system microcontroller or processor in a complete system and has been included for no other purpose than to demonstrate the TAS5404-Q1 capabilities; therefore, this document does not describe it in full detail. Note that the TAS1020B is not AEC Q100 qualified. Texas Instruments (TI) does not recommend the use of this device for new designs.

3.1.1 TAS5404-Q1

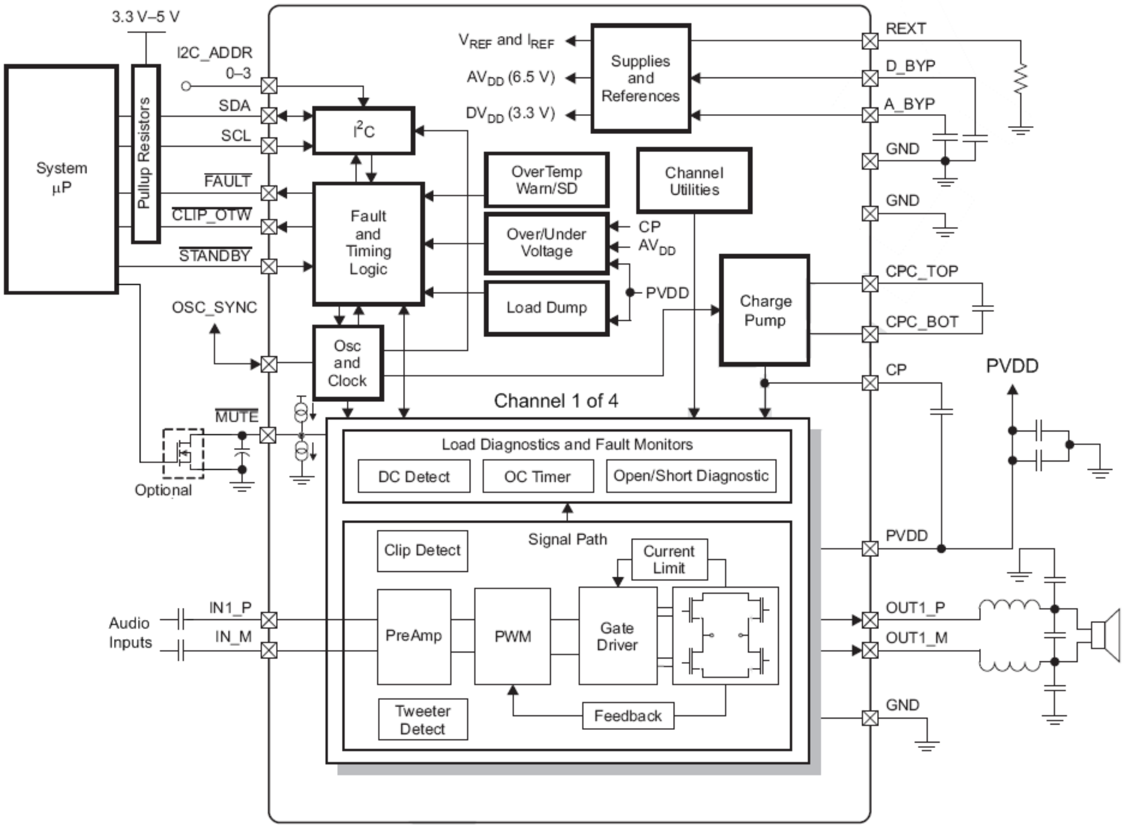

Figure 3. 25-W, Analog, Single-Ended Input, 4-Ch, Class D Amp With Load Dump Protection and I²C Diagnostics

- Output power: 4 W × 22 W at 4 Ω, 1% THD+N, 14.4 V
- Input range 5.6 V to 18 V (operational during cold, crank, start, and stop events)
- 50-V load dump and over temperature protection
- Automotive electromagnetic interference (EMI) performance (CISPR25 Class 5)
- I²C load diagnostics (shorts, open, and tweeter)
- Programmable switching frequency (357 kHz, 417 kHz, and 500 kHz) for AM band avoidance
- Lineout mode: From a few Ω to several kΩ
- Fully AEC-Q100 qualified and TS16949 certified

3.1.2 TL760M33-Q1

- Load-dump protection
- Qualified for automotive applications
- ±3% output voltage variation across load and temperature
- 500-mV maximum dropout voltage at 500 mA
- Fixed 3.3-V output
- Internal thermal overload protection
- Internal overvoltage protection

4 System Design

As the block diagram in the previous Figure 1 shows, the design consists of two separate parts: a daughterboard (see Figure 4) and a motherboard (see Figure 5), which have been soldered together through the dual row connector.

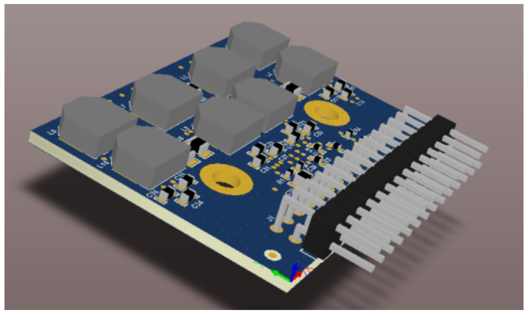

Figure 4. Daughterboard—3D View

The daughterboard encompasses the Class D amplifier solution in a small form factor comparable to Class AB devices. The motherboard is a base board simulating a part that is normally in the head unit to show the functionality of the daughterboard.

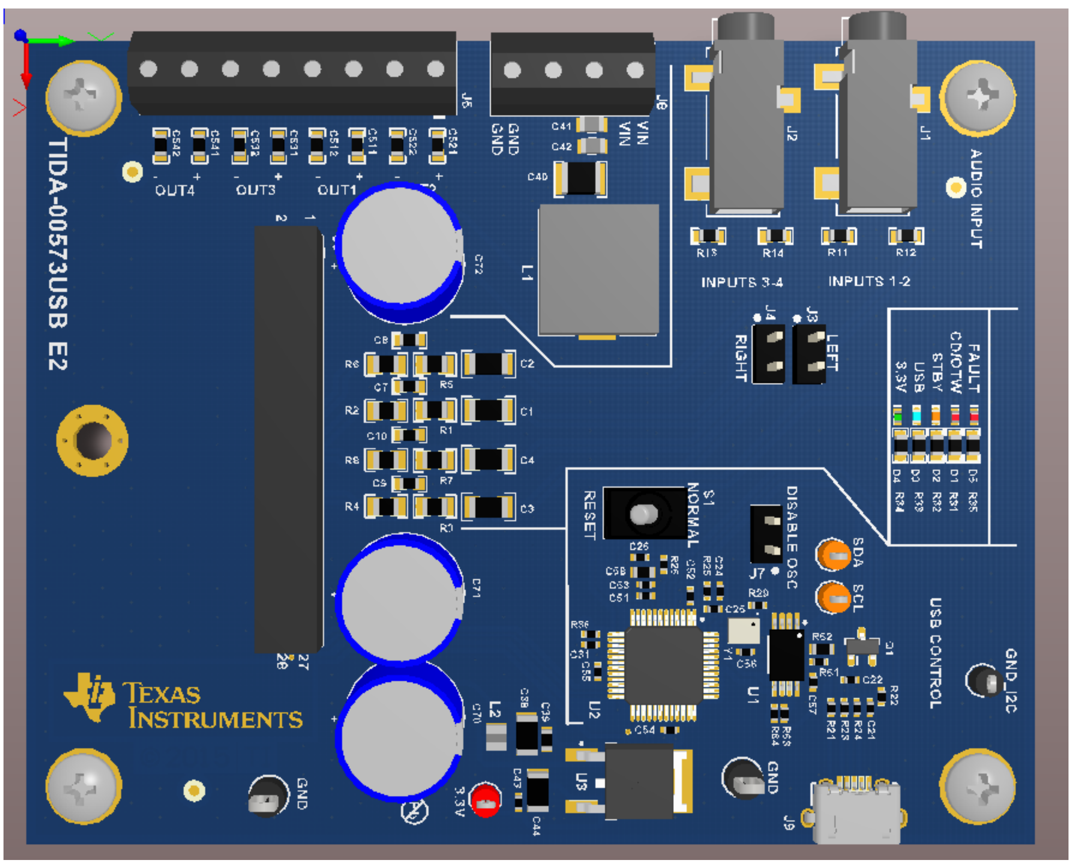

Figure 5. Motherboard—3D View

4.1 Daughterboard Circuit Design

4.1.1 Class D Output Filter

An audio signal modulates the PWM output in a Class D amplifier, which results in a combination of the audio band plus the switching frequency at the amplifier output. To filter the PWM switching frequency, a low-pass filter with a cutoff frequency lower than the switching frequency is applied in the output.

The TAS5404 has bridge-tied load (BTL) amplifier outputs . A low pass filter is required for the positive and negative outputs to filter the PWM frequency. Additionally, to filter the common mode and provide high-frequency decoupling, a capacitor (C_g) has been employed on each side of the load to ground. Figure 6 shows a typical output schematic.

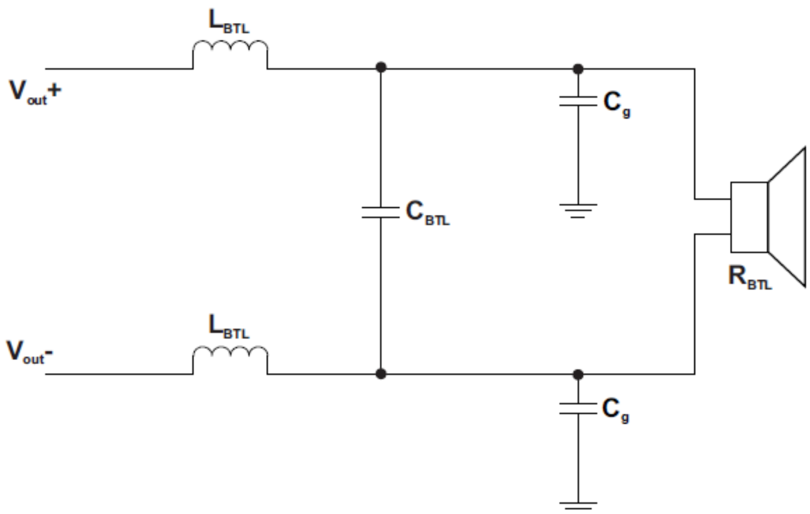

Figure 6. Diagram of Typical Class D Amplifier Output Filter

Equation 1 and Equation 2 are used to calculate the filter component values:

$$C_{BTL} = C_g = \frac{2Q^2 L_{BTL}}{R_{BTL}^{\ 2}} \quad (1)$$

$$L_{BTL} = \frac{R_{BTL}}{4\pi f_c Q} \quad (2)$$

The speaker load resistance determines the variable L_{BTL}. The load, desired cutoff frequency and desired filter Q value determine the value for the capacitors C_g and C_{BTL}. In a second-order, low-pass Butterworth filter, the circuit is critically damped when Q = 0.707. See Figure 7 for a plot of the effect of different damping factors.

The values selected in this design are:

- Q = 0.707
- f_c = 45 kHz
- R_{BTL} = 4 Ω

$$L = \frac{4}{4\pi \times 45000 \times 0.707} = 10\ \mu H \quad (3)$$

$$C_{BTL} = \frac{2 \times (0.707)^2 \times 10\ \mu}{4^2} = 0.62\ \mu F \quad (4)$$

The capacitance value chosen for the design is 0.68 µF because this is a standard value. This capacitance value has no negative impact on the EMI performance.

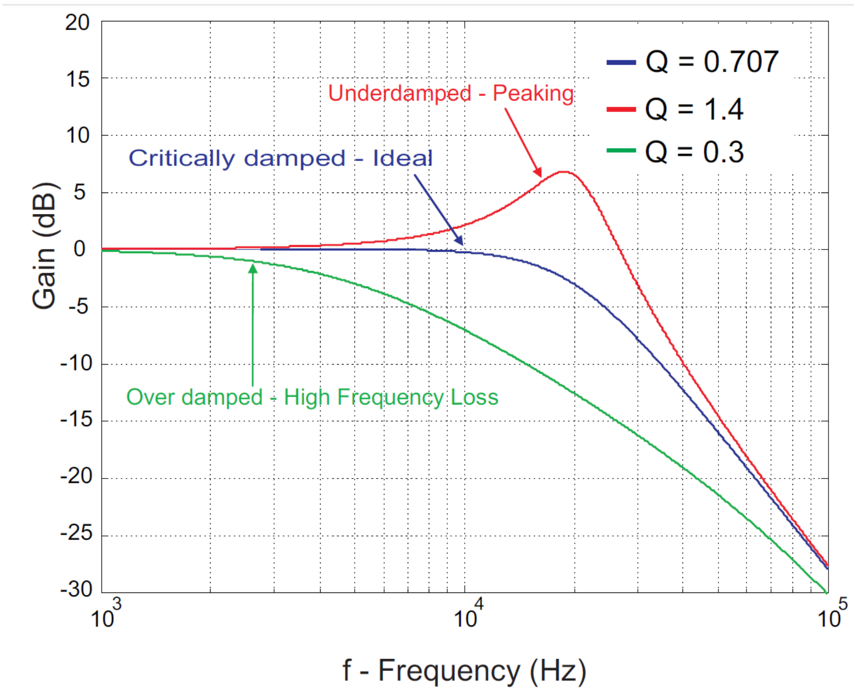

Figure 7. Filter Damping (Q Factor)

Figure 8 shows a schematic for one output channel with the inductor and capacitor values calculated from Equation 1 and Equation 2.

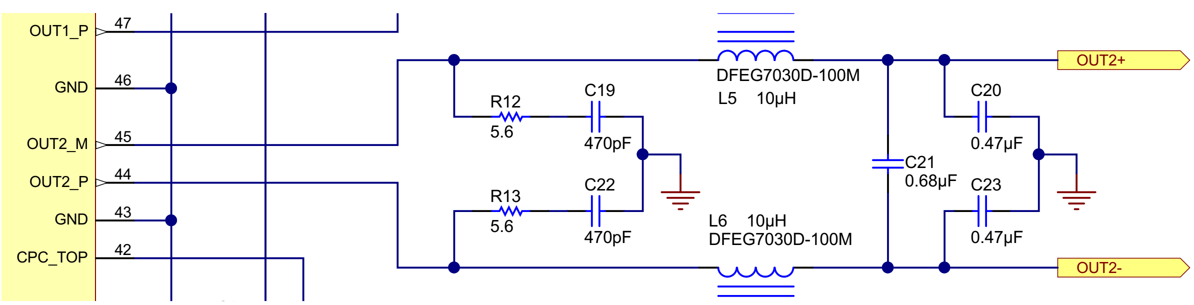

Figure 8. Output Filter in OUT2

4.1.2 Metal Alloy Inductors

One of the key parameters for this design is the total size of the daughterboard. The use of small inductors is desirable because they reduce circuit board size. Metal alloy inductors present benefits of smaller size, better temperature stability, higher current capability, and low leakage flux in comparison to ferrite inductors, which are typically used in circuits.

As the following Figure 9 shows, the variation of inductance is not significant as the temperature rises. This characteristic makes metal alloy inductors very stable over temperature. The inductance drop is small over a larger current swing. This characteristic is necessary in Class D amplifiers to maintain inductance in the output filter over all current levels. If the inductance drops to a low level, the overcurrent protection may trigger unexpectedly.

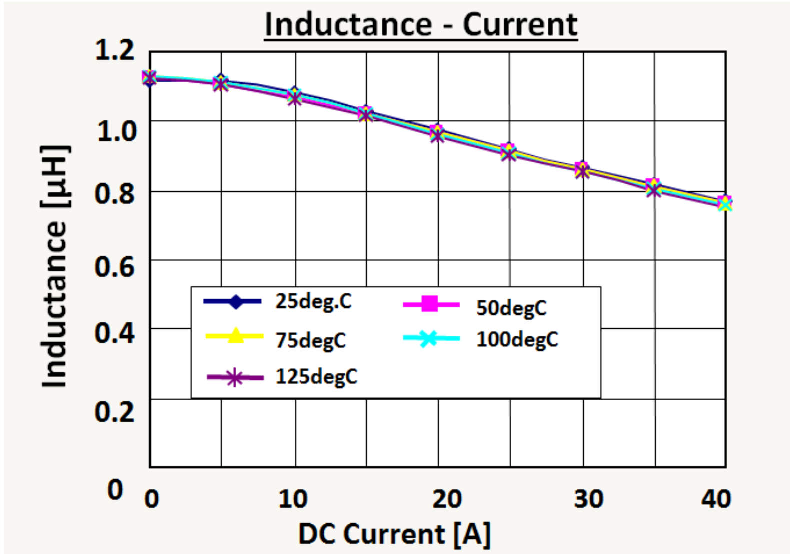

Figure 9. Inductance Versus Current in Metal Alloy Inductor

4.2 *Motherboard Circuit Design*

The motherboard encompasses what is typically included in a head unit and has been designed to showcase the performance of the daughterboard.

The motherboard features:

- Input filter
- USB controller
- Basic GUI for diagnostics
- Power management
- Input and output connectors

4.2.1 Input Filter

The input filter features the DC blocking caps; a first-order, low-pass RC filter towards the input a decade above the audio band; and a first-order, low-pass RC filter towards the connector for the return signal that the user may receive from the device.

One important thing to note is that the total impedance of the input must match the impedance of the return input on the TAS5404-Q1 device (IN_M) as specified in the TAS5404-Q1 datasheet SLOS918.

Figure 10 shows jumpers J3 and J4 that have been provided to tie the right channels and left channels together, which allows the user to drive the four Class D amplifiers with only one stereo jack input.

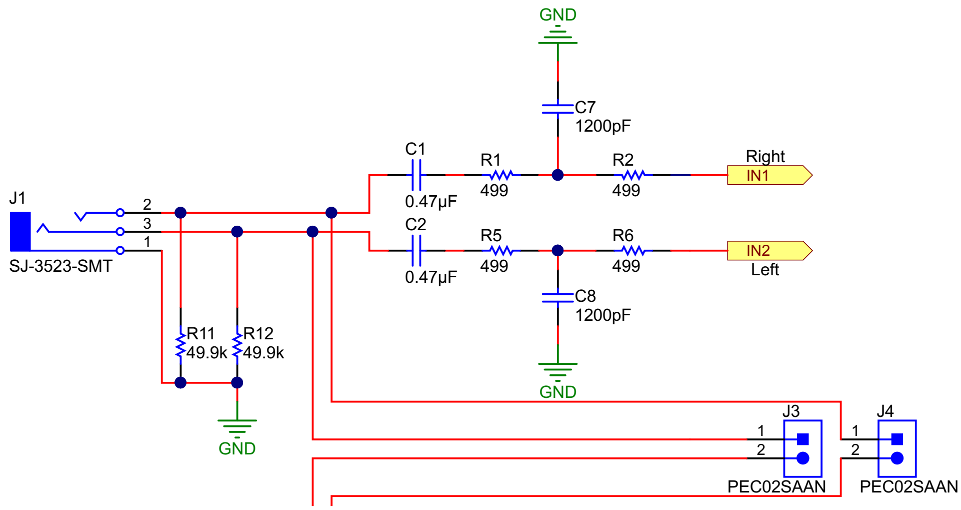

Figure 10. Input Filter

4.2.2 Output Connector and Filter

To filter high frequencies and improve EMI performance, capacitors have been added next to the output connector, which creates a low-impedance path for high frequency signals (see Figure 11).

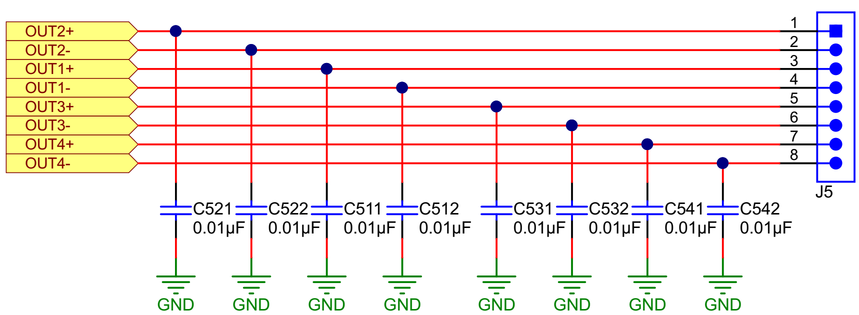

Figure 11. Filter at Connector

5 Getting Started

The following procedure assumes that the TAS1020B (U2 on the USB board) is populated.

To get started with the TIDA-00573, connect the power leads to the four-terminal connector (J8) in the labeled polarity shown in Figure 12. TI recommends using two wires for each power connection. Note that the screw terminal accepts 22 AWG wire.

Connect a power supply to the leads. *Do not turn on the power supply at this point*.

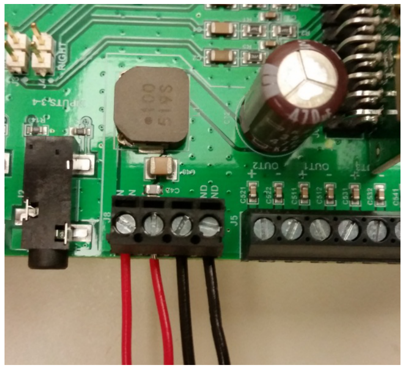

Figure 12. Step 1—V_{IN} Input Connection

Connect the USB cable to the PC and J9 through the micro-USB connector (see Figure 13). Make sure that the jumper in J7 has been removed and that switch S1 has been set for NORMAL operation.

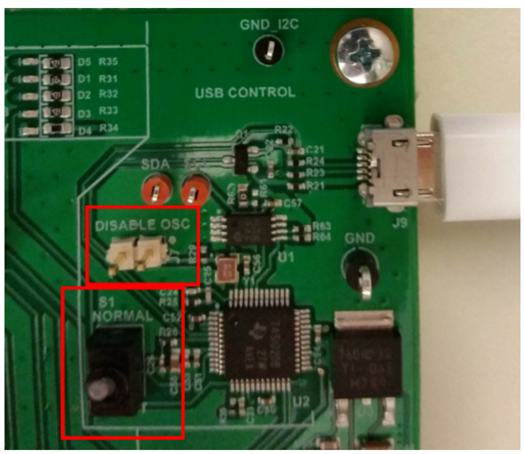

Figure 13. Step 2—Micro-USB Connection

Connect the loads or speakers through the J8 output connectors. Note that the plus and minus of every channel are labeled and the order of the channels from top to bottom is 2, 1, 3, 4. These terminals accept 22 AWG wires.

Connect the input 3.5-mm female jack to the input connectors. The user can short the two stereo jacks using jumpers in J3 and J4 as discussed in Section 4.2.1 This ties the right and left channels together so that only one stereo jack is required to provide a signal to the four channels of the amplifier.

Now set the power supply to the desired voltage (typically 14.4 V) and apply power to the TIDA-00573. The green light-emitting diode (LED) D4 labeled “3.3V” and the blue LED D3 labeled “USB” should now turn on. After this step, the board is ready to be controlled by the GUI.

6 Graphical User Interface

The following procedure assumes that the TAS1020B (U2 on the USB board) has been populated.

The GUI utilizes the TI Purepath™ Console 3 (PPC3) Software. Download the GUI from http://www.ti.com/tool/PUREPATHCONSOLE.

The TAS5404Q1EVM GUI is downloadable through the PPC3 platform. Any updates automatically display for download. Connect the PC to the internet to use this function.

Figure 14 displays the GUI. Connect the GUI to the EVM by clicking the *Connect* button at the bottom left of interface. Upon a successful connection the small circle turns green and the *Connect* button disappears.

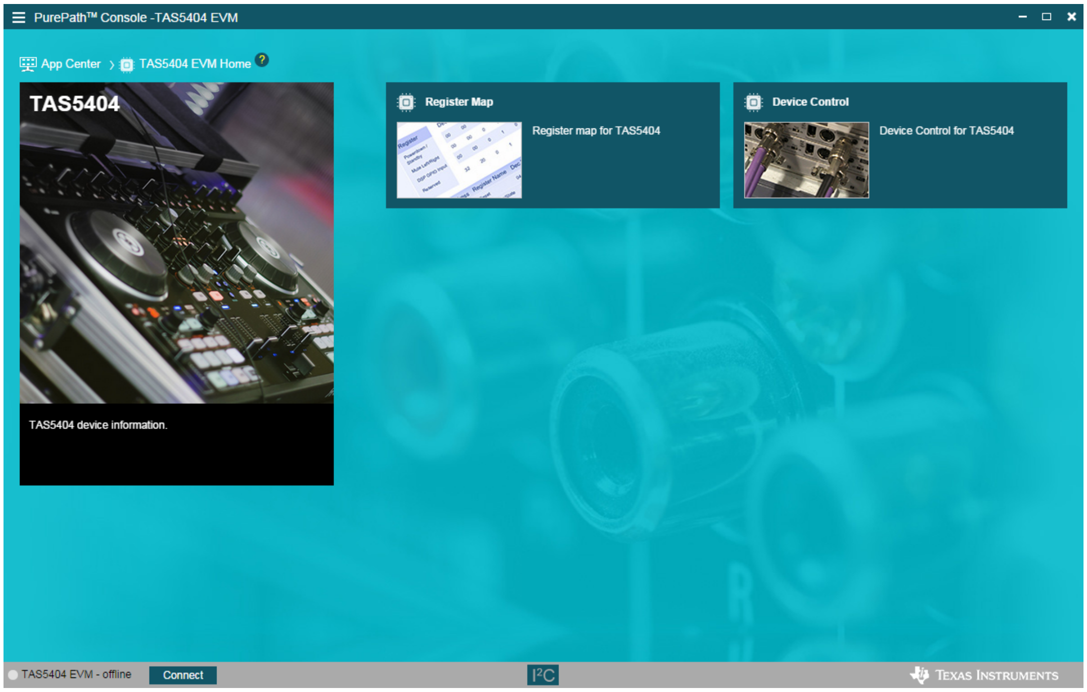

Figure 14. TAS5404 EVM GUI Home Page

6.1 Register Map Page

Click on the *Register Map* menu heading located at the top of the *Home* page to display the register map of the TAS5404-Q1 device. Opening the page reads all registers and populates the registers with the TAS5404-Q1 register defaults.

Figure 15 displays the *Register Map* page. Click on the register to display the description in the *Fields* column. In the *Register Map* table, the pink values are read only and the black values can be changed and written to the device. Double click on a black value to change its state and write the value to the device. Reference the TAS5404-Q1 datasheet, SLOS918, for complete descriptions of the registers and their functions.

Click on the *TAS5404 EVM Home* menu heading above the *Register Map* table to return to the *Home* page.

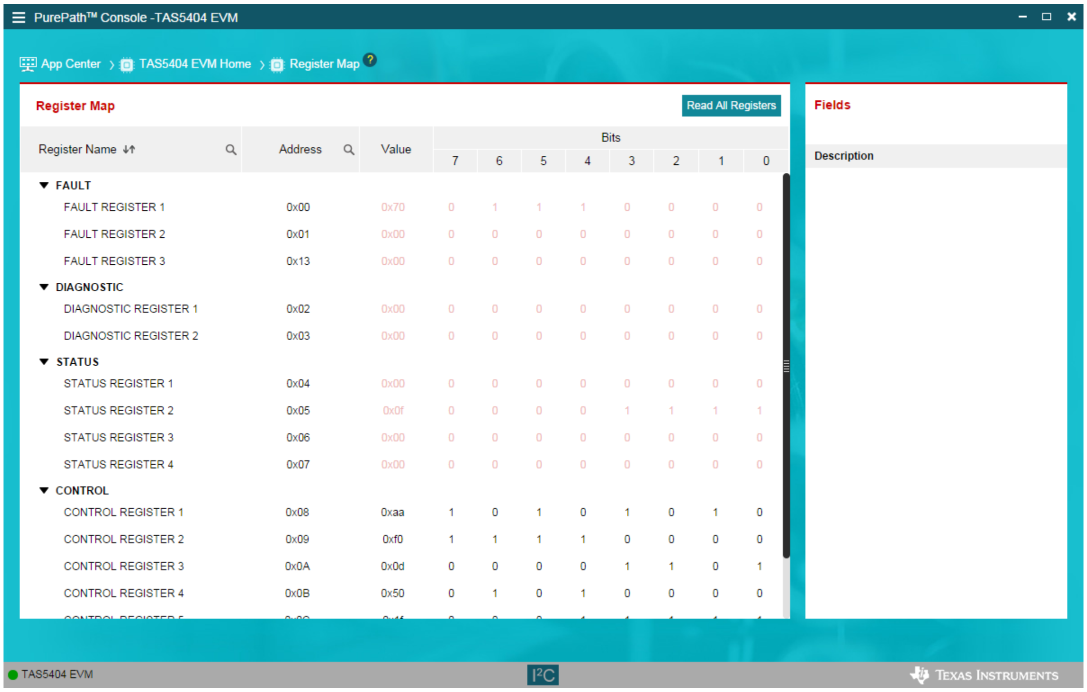

Figure 15. Register Map Page

6.2 Device Control Page

Enter the *Device Control* page by clicking on the *Device Control* menu heading located at the top of the *Home* page. The page shown by Figure 16 displays. This page has buttons that control certain functions of the TAS5404-Q1 device.

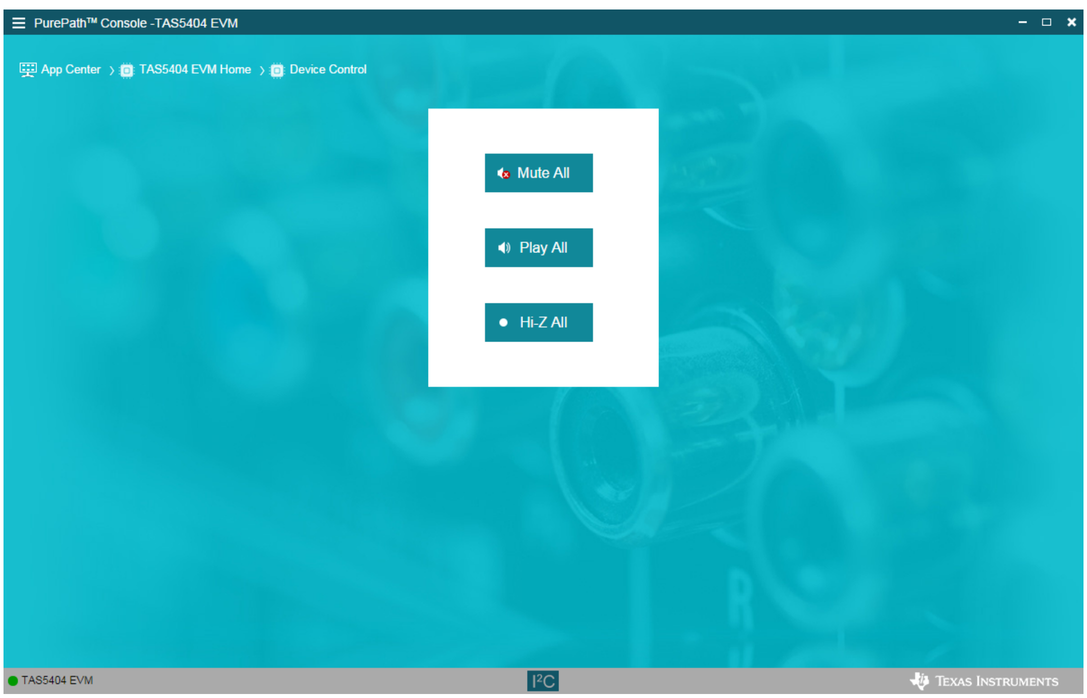

Figure 16. Device Control Page

7 PCB Layout Guidelines

Several critical items must be considered in the circuit board layout to optimize noise and EMI performance:

- A heatsink must make contact with the top of the amplifier IC. Ensure that components placed nearby do not interfere with the heatsink.
- The decoupling capacitors must be physically close to the TAS5404-Q1. The decoupling capacitors are C10, C11, C37, and C38 in this design (see Figure 19).
- The snubber circuits must be placed as close as possible to the TAS5404-Q1 to reduce the AC current path (see Figure 17).

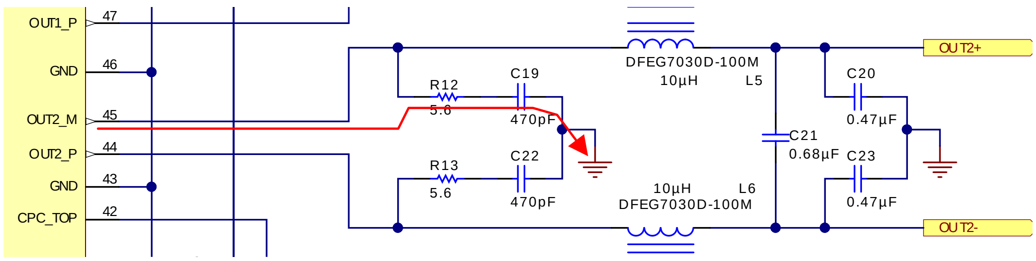

Figure 17. AC Current Path in Snubber Circuits

- The common-mode filter capacitors C20 and C23 must share a common ground in the same plane. The ground pins for these capacitors must be placed very close to a via to minimize the loop inductance for these capacitors (see Figure 18).

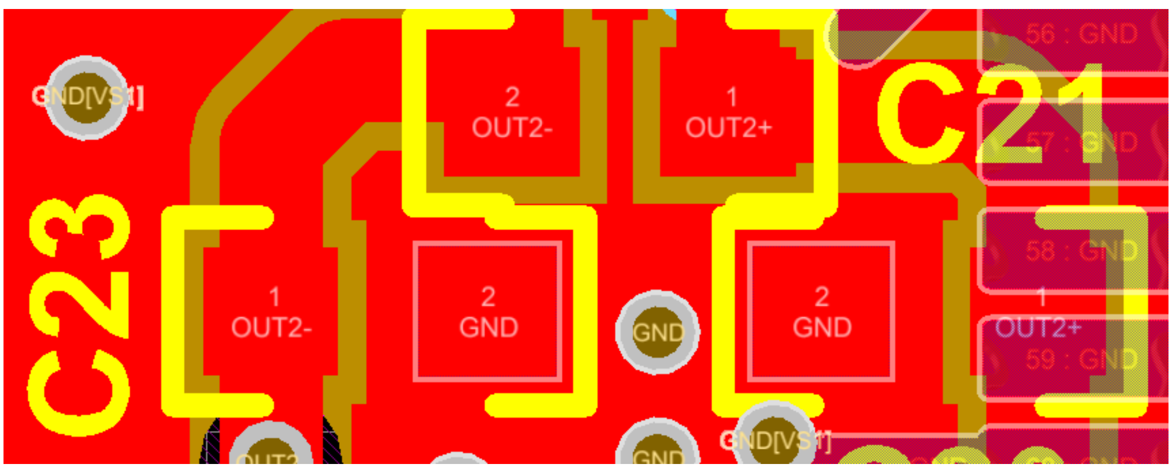

Figure 18. Common-Mode Capacitors Layout

- TI recommends via stitching across the entire ground plane to reduce the ground impedance.
- TI recommends that the output filter inductors be placed close to the TAS5404-Q1 to reduce the trace impedance.

The boxed-in areas in Figure 19 indicate the outputs. The image on the left side of the figure emphasizes the output filters and the right-side image shows the snubber circuits.

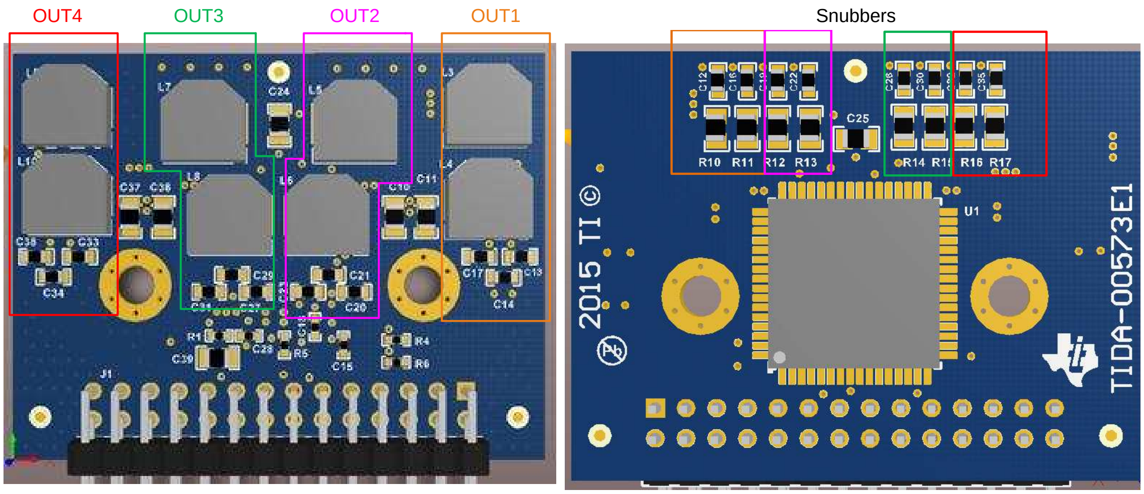

Figure 19. Placement of Components—Daughterboard

The grounding between the signal inputs on the motherboard and the daughterboard has been reinforced by a trace that connects them to avoid any difference in the grounding created by the resistance of the connector or interferences from other signals (see Figure 20). With the purpose of avoiding a difference in the grounding between the daughterboard and the signal inputs on the motherboard created by the resistance of the connector or interferences from other signals, this ground was reinforced by a trace connecting them.

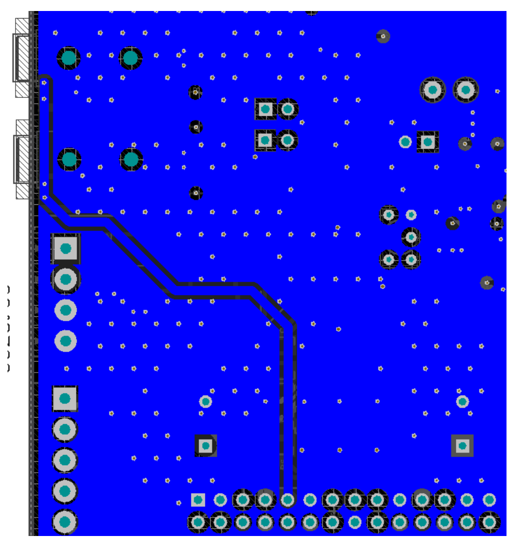

Figure 20. Ground Trace on Bottom Layer

TI recommends routing the amplifier output + and – signals on adjacent layers with the traces overlapped as much as possible. Routing the signals in this way helps to cancel EMI from the output sections. Keeping the output routes on inner layers of the circuit board also improves EMI performance if the outer layers have ground fills over the traces. Figure 21 shows the routing of the output signals.

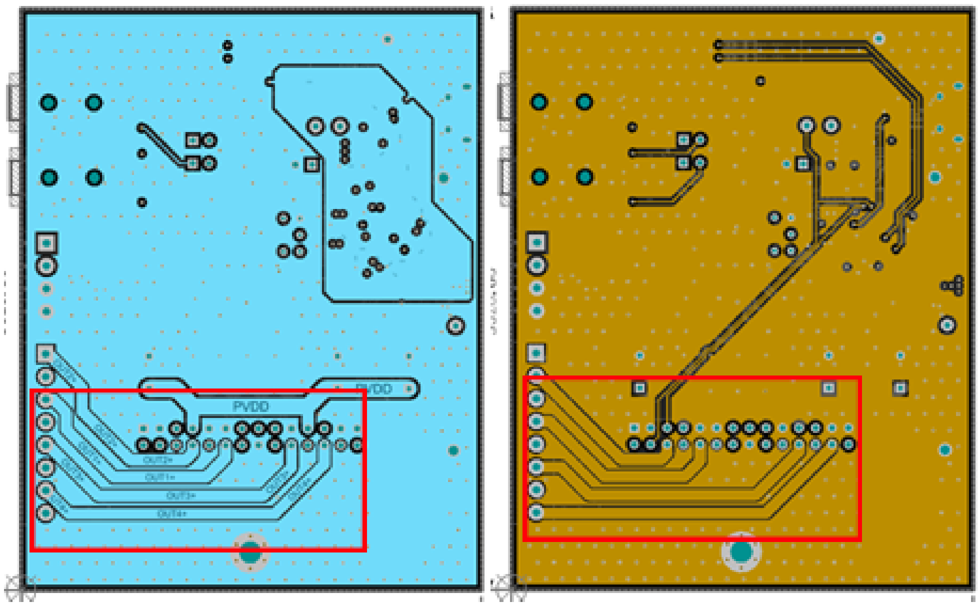

Figure 21. Output Signal Traces Overlap for Current Cancellation in Layer 2 and Layer 3

8 Test Results

The diagrams in the following subsections show the results for various tests. Unless otherwise noted, the output loads for all tests are 4-Ω resistors with power ratings of 50 W or higher.

8.1 Crosstalk

Setup

The input signal is inserted in a particular channel while shorting the others. The coupled signal is measured in all of the channels that are not driven (see Figure 22).

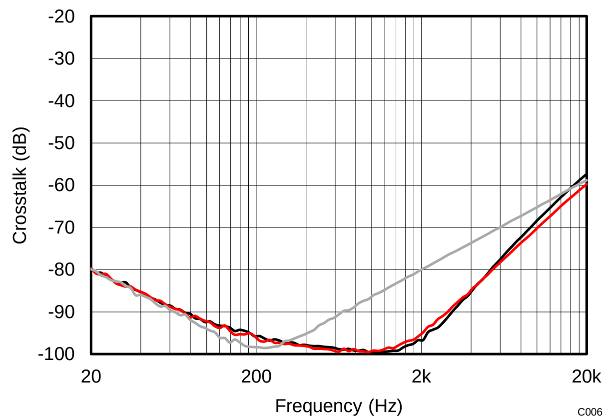

Figure 22. Crosstalk—Channel 1 Driven

8.2 THD+N Versus Frequency at 1 W

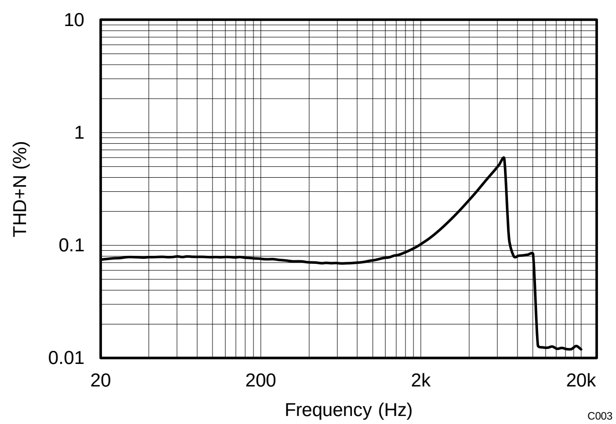

Figure 23. THD Versus Frequency at 1 W into 4 Ω

8.3 THD+N Versus Power at 1 kHz

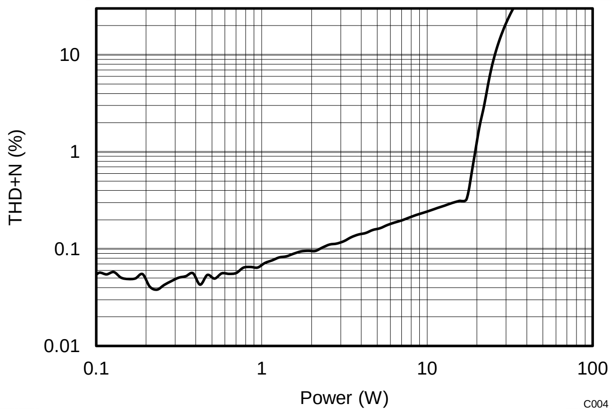

Figure 24. THD+N Versus BTL Output Power at 1 kHz into 4 Ω

8.4 Efficiency

The following Figure 25 shows the efficiency measurements for the device (TAS5404-Q1) and the TIDA-00573 board.

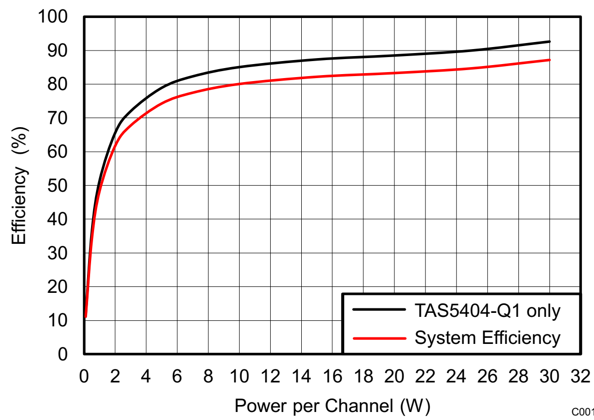

Figure 25. Efficiency of Device and System

8.5 Thermal

To analyze the thermal performance of the design, a comparison with a class AB amplifier has been conducted using the exact same heatsink and running the four channels simultaneously at 1 W. The units for temperature are in °C. The thermal tests have been conducted at an ambient temperature of 25°C.

Class D

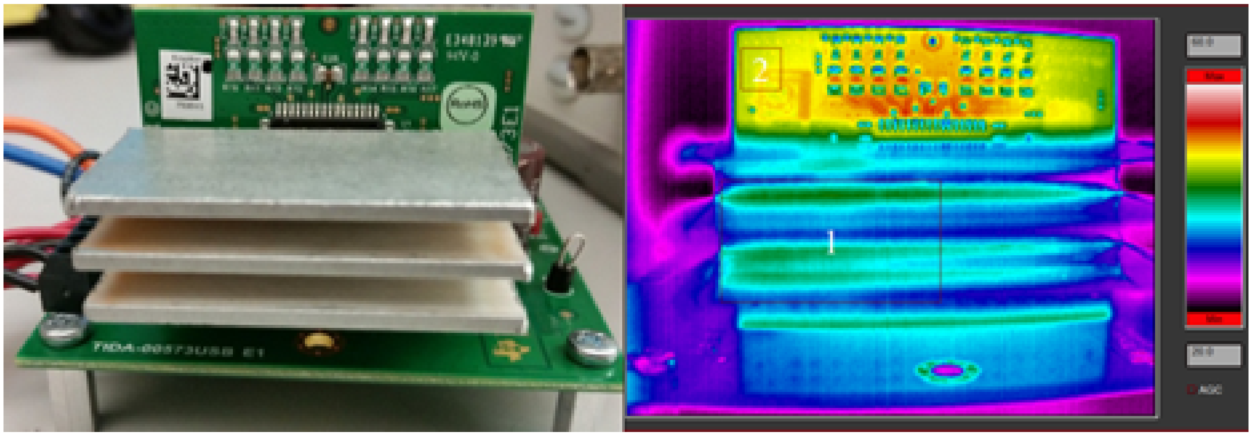

Figure 26. Thermal Measurement of Class D Amplifier—Front

Zone 1: 28.89°C (min), 36.20°C (avg), 42.32°C (max)

Zone 2: 45.75°C (min), 46.91°C (avg), 48.78°C (max)

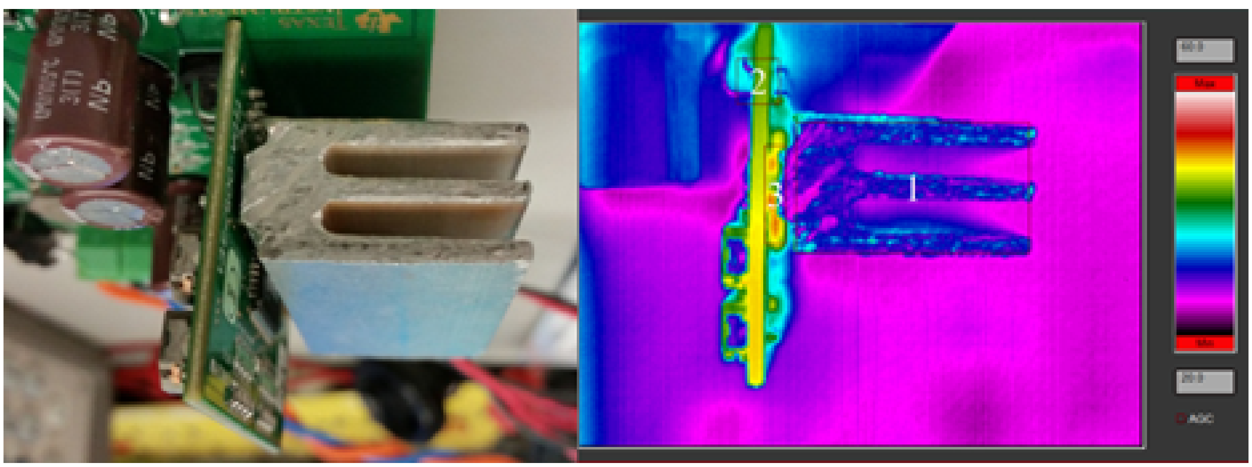

Figure 27. Thermal Measurement of Class D Amplifier—Side

Zone 1: 24.00°C (min), 29.57°C (avg), 39.85°C (max)

Zone 2: 27.40°C (min), 38.73°C (avg), 44.93°C (max)

Zone 3: 26.47°C (min), 44.01°C (avg), 50.54°C (max)

Class AB

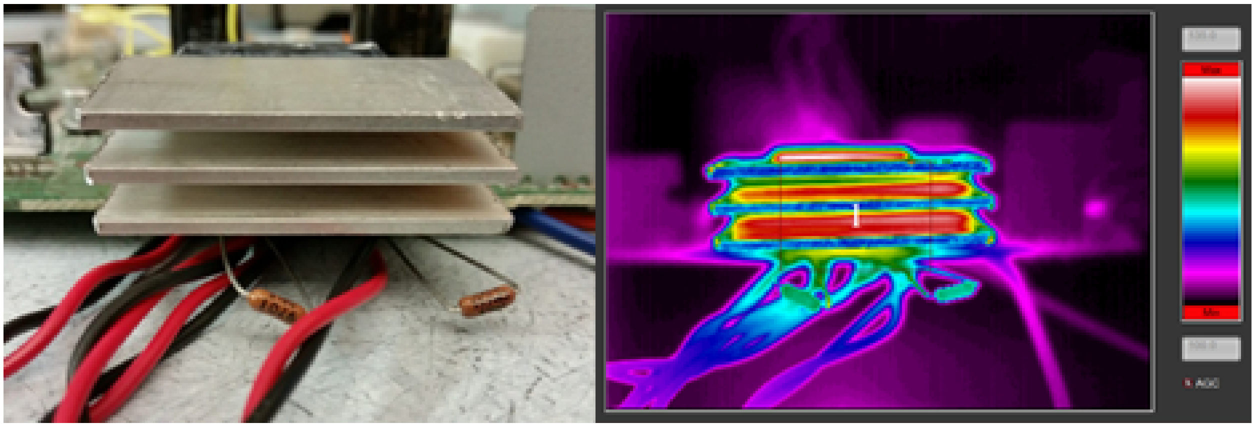

Figure 28. Thermal Measurement of Class AB Amplifier—Front

Zone 1: 27.12°C (min), 80.13°C (avg), 114.15°C (max)

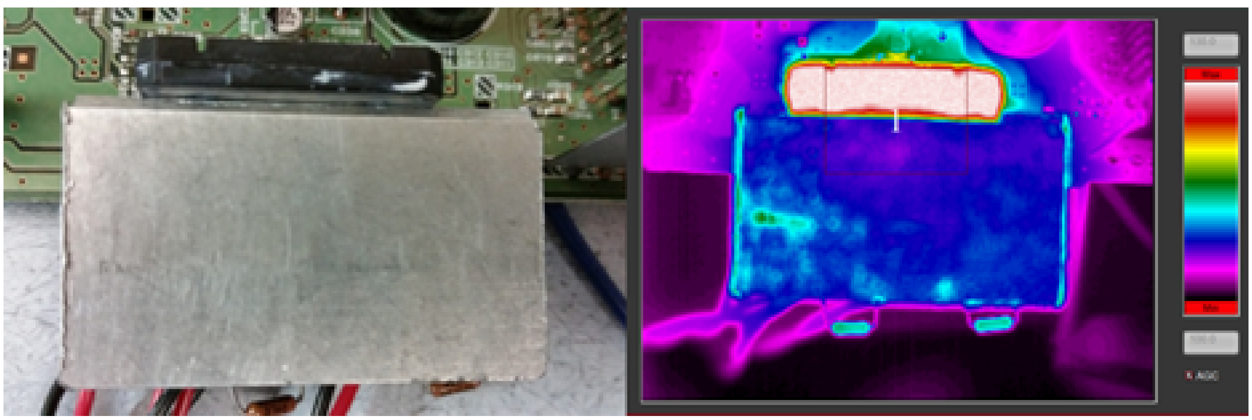

Figure 29. Thermal Measurement of Class AB Amplifier—Side

Zone 1: 42.11°C (min), 86.32°C (avg), 133.46°C (max)

Maximum Class D: 50.54°C

Maximum Class AB: 133.46°C

The previous figures show that the Class D amplifier is much cooler than the Class AB amplifier operating under the same conditions.

8.6 Load Dump Test—ISO7637 Pulse 5b

The board has been designed to withstand a 50-V load dump pulse in accordance with ISO7637-2:2004 Pulse 5b specification. According to the specification, this transient occurs in the event of a discharged battery being disconnected while the alternator is generating charging current and with other loads remaining on the alternator circuit.

Figure 30 shows the load dump profile. The test has been performed in the worst case scenario for a 12-V battery:

- V_{IN} = 14.4 V
- U_S = 87V
- t_d = 400 ms
- t_r = 10 ms
- Suppressed voltage (U_S*) = 35.6 V

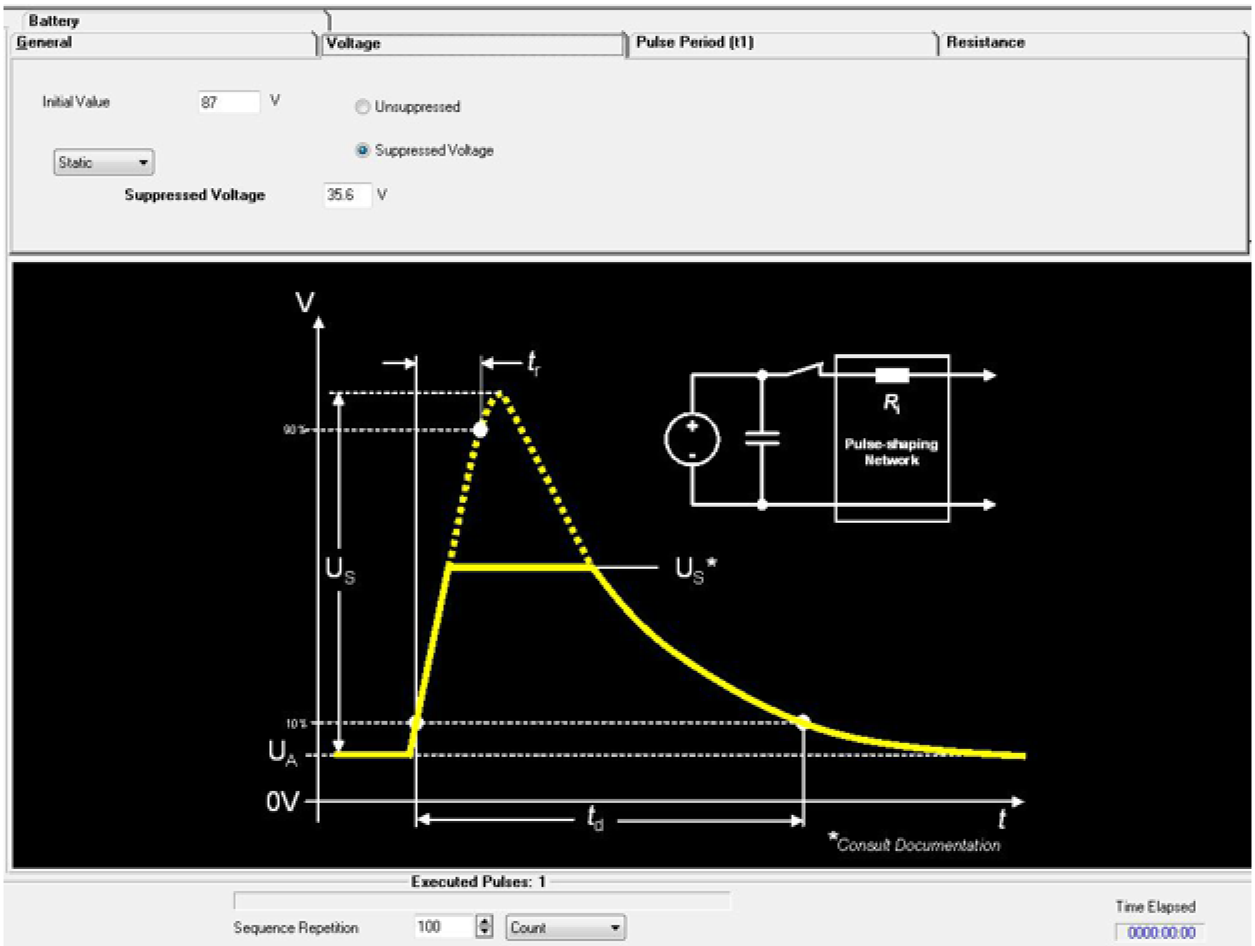

Figure 30. Load Dump Pulse 5b Configuration

A stress test of 100 repetitions with the aforementioned configuration has been conducted without causing any damage or causing the device to fail.

8.7 CISPR 25 Class 5—EMI Test

Automotive infotainment equipment designers have been reluctant to use Class D amplifiers in their systems because of EMI concerns. This TI Design has been tested to CISPR 25 Class 5 limits to eliminate these concerns. Table 2 shows the specification limits, measured values, and margin at which the design passes the CISPR 25 Level 5 specification.

Table 2. CISPR 25 Limits and Test Results

SERVICE/BAND	FREQUENCY (MHz)	LEVEL IN dB (uV/m)			
		CISPR 25 CLASS 5 LIMITS		MEASURED VALUES	
BROADCAST		PEAK	AVERAGE	AVERAGE	MARGIN
LW	0.15 to 0.30	46	26	22.4	3.6
MW	0.53 to 1.8	40	20	17.9	2.1
SW	5.9 to 6.2	40	20	5	15
FM	76 to 108	38	18	5	13
TV band I	41 to 88	28	18	4	14
TV band III	174 to 230	32	22	4	18
DAB III	171 to 245	26	16	4	12
TV band IV/V	468 to 944	41	31	11	20
DTTV	470 to 770	45	35	15	20
DAB L band	1447 to 1494	28	18	3	15
SDARS	2320 to 2345	34	24	6	18

9 Design Files

9.1 Schematics

To download the schematics, see the design files at TIDA-00573.

9.2 Bill of Materials

To download the Bill of Materials (BOM) for each board, see the design files at TIDA-00573.

9.3 Layout Prints

To download the layout prints, see the design files at TIDA-00573.

9.4 Altium Project

To download the Altium project files, see the design files at TIDA-00573.

9.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00573.

9.6 Software Files

To download the GUI for I^{2}C communication, visit http://www.ti.com/tool/PUREPATHCONSOLE.

10 References

1. Texas Instruments, *TAS5404-Q1: 26-W Analog Single-Ended Input 4-Channel Class-D Amp with Load Dump Protection and I^{2}C Diagnostics*, TAS5404-Q1 Datasheet (SLOS918)
2. Texas Instruments, *TAS1020B USB Streaming Controller*, TAS1020B Data Manual (SLES025)
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4. Texas Instruments, *LOW-DROPOUT FIXED-VOLTAGE REGULATORS* , TL760M33-Q Datasheet (SGLS284)
5. Texas Instruments, *USB Interface Adapter Evaluation Module*, USB-TO-GPIO User's Guide (SLLU093)
6. ISO.org, *ISO 7637-2:2011 Road vehicles – Electrical disturbances from conduction and coupling – Part 2: Electrical transient conduction along supply lines only*, Section 5.6 http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=50925
7. ISO.org, *ISO 16750-2:2012 Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 2: Electrical loads*, Section 4.6 http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=61280

11 About the Author

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