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A Guide To Power Electronics Design For Off-Battery Automotive (Part 1): EMC And Line Transient Requirements

by Timothy Hegarty, Texas Instruments, Phoenix, Ariz.

Efforts to improve the driving experience and safety have dramatically increased the number of embedded electronic systems in a typical vehicle environment. Reliable, automotive-grade dc-dc regulator solutions are crucial to the development of the automotive ecosystem, powering critical loads such as advanced driver assistance systems, body electronics and lighting, infotainment and cluster, and innovative safety technologies.[1, 2] As a result, the automotive electrical system and its reliability in harsh automotive environments has become more important.

Given the increasing number of power electronic systems integrated within vehicle designs, it is essential to consider the complicated electrical and electromagnetic environment in which these systems operate. All vehicle original equipment manufacturers (OEMs) and most component suppliers to the OEMs perform tests to verify the electromagnetic compatibility (EMC) of their devices.

In a previous 18-part series published in How2Power Today,[3] I discussed requirements related to conducted emissions (CE) and radiated emissions (RE). However, there is another area of EMC that is equally important and it encompasses three types of immunity—conducted immunity (CI), radiated immunity (RI) and electrostatic discharge (ESD) immunity—which you should understand before tackling an automotive power design. Thus, in part 1 of this article series, I will discuss the immunity, ESD and supply-line transient requirements associated with conventional vehicle electrical systems, both 12 V and 24 V.

I'll begin by briefly identifying the relevant CISPR and ISO standards that govern RI, CI and ESD performance in automotive applications at the vehicle, component and subassembly levels. I'll also call out relevant internal specifications required by the various automotive OEMs.

Then I'll delve into specific test requirements of ISO 16750-2 for power line quality, ISO 7637-2 for electrical transient conduction along supply lines, ISO 11452 for narrowband RI and ISO 10605 for ESD immunity. The discussion on ISO 16750-2 covers supply voltage transient profiles such as the waterfall test, cold and warm crank and start-stop profiles, and load dump.

EMC Compliance

EMC compliance requires that an electronic or electromechanical product comply with laws, directives and regulations of the country or region where it is sold. For example, United Nations Economic Commission for Europe (UNECE) Regulation 10[4] requires OEMs to gain type approval for the complete vehicle, in addition to the electrical or electronic subassemblies (ESAs) that make up the vehicle's total electrical system.

All devices should function satisfactorily in the electromagnetic environment without introducing intolerable electromagnetic disturbances to other systems in that environment.

Table 1 summarizes international EMC specifications from Comité International Spécial des Perturbations Radioélectriques (CISPR) and the International Organization for Standardization (ISO) directed to vehicles, components or ESAs using 12- or 24-V battery systems. Regulatory requirements such as UNECE Regulation 10.06 do refer to these CISPR and ISO specifications as needed.

In addition, most automotive OEMs require compliance with their own internal specifications for ESAs used in their vehicles. Examples include GMW3097,[5] FMC1278,[6] CS.00054 and JLR-EMC-CS,[7] from General Motors, Ford, Stellantis and Jaguar Land Rover, respectively. These documents refer to CISPR and ISO specifications for CE, RE, CI, RI and ESD testing, with differences in scope or test levels as defined by the OEM.

Table 1. EMC specifications from CISPR and ISO for vehicle- and component or ESA-level testing.

EMC disturbance	**Vehicle-level tests**	**Component- or ESA-level tests**
Conducted emissions	-	CISPR 25 (protection of onboard receivers)
Radiated emissions	CISPR 12 (protection of offboard receivers)	
Conducted transient emissions (CTE), conducted transient immunity (CTI), supply-line transient disturbances	-	ISO 7637, ISO 16750
Radiated immunity	ISO 11451	ISO 11452
Electrostatic discharge	ISO 10605	ISO 10605

Within the context of off-battery dc-dc regulators (see the system block diagram shown in Fig. 1), let's now examine these ISO specifications for immunity requirements: ISO 16750-2[8-10] and ISO 7637-2 for CI,[11] multiple parts of ISO 11452 for RI,[12] and ISO 10605 for ESD.[13, 14]

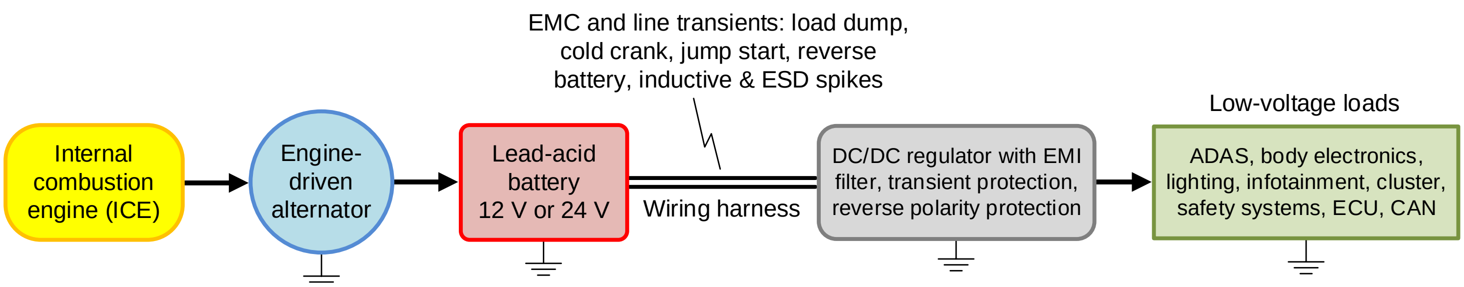

Fig. 1. Functional block diagram of an automotive electrical system, including dc-dc conversion to power low-voltage loads.

The test methods described in these ISO specifications determine the ability of a given system (and, by extension, its power stage) to meet applicable EMC specifications. I recommend reviewing CISPR 25 separately for an understanding of emissions requirements by referring to parts 1, 2 and 4 in reference [3].

ISO 16750-2—Power-Line Quality

Table 2 summarizes the applicable immunity tests included in the scope of ISO 16750-2.[8] Relevant test parameters denoted in parentheses in Table 1 refer to 24-V electrical systems (where applicable). While typically the most demanding tests defined in ISO 16750-2 are cold crank and load dump, ISO 16750-2 includes many additional tests.

Table 2. ISO 16750-2 related tests for power-line quality in automotive battery systems, 12 V (24 V) nominal.

Test	**Origin of test**	**Test parameters**	**Section**
Dc supply voltage range	Battery dc voltage variation over load, temperature and state of charge	V_{Smax} = 16 V (32 V), V_{Smin} = 6 V (10 V)	4.2
Overvoltage—alternator fault	Alternator's voltage regulator faults, causing full application of charging current to the battery	18 V (36 V) for 1 hour at 20°C below T_{MAX}	4.3
Overvoltage—double-battery jump-start	Jump-start from a commercial vehicle with a dual-battery electrical system	24 V for 2 minutes, room temperature	4.3.1.2
Superimposed alternating voltage	Ac voltage riding on the dc battery voltage because of the alternator's three-phase bridge-rectified output voltage ripple	1 V, 2 V or 4 V (1 V, 4 V, 10 V) peak-to-peak severity level at a 50-Hz to 25-kHz frequency sweep for 2 minutes, 5 sweeps in total	4.4
Slow change of supply voltage	Slow decrease and increase of the battery voltage	Discharged from V_{Smin} to 0 V and then brought back up with a 0.5-V-per-minute slew rate	4.5
Drops in supply voltage	Failure in another circuit that causes the supply to dip	Supply voltage dips from V_{Smin} to 4.5 V (9 V) for 100 ms and then recovers; rise and fall times are ≤10 ms	4.6.1
Reset behavior at voltage drop	"Waterfall" test verifies the reset behavior of the device under test (DUT) at different voltage drops	See Fig. 2	4.6.2
Starting profiles	Battery voltage drop and subsequent recovery upon engaging the starter motor during cold crank, warm crank or start-stop	Initial low-voltage plateau as low as 3 V (6 V) for 15 ms during cold crank; see Fig. 3	4.6.3
Load dump	Disconnection of a discharged battery from an alternator operating at a high current	Clamped to U_S* = 35 V (58 V), subject to the alternator's centralized clamp and the regulator response time; 10 pulses at 1-minute intervals	4.6.4
Reversed battery voltage	Negative voltage applied by misconnection at the battery terminals	−14 V (−28 V) for 1 minute	4.7.2.3
Open circuit	Open-contact condition—single- and multiple-line interruption tests	Verify that the device resumes normal operation when connection is removed, then restored	4.9
Short-circuit protection	Short circuit to the inputs and outputs of a device	Connect each input and output to V_{Smax} (the maximum supply voltage) and ground for 1 minute	4.10

The next section details the most challenging supply-voltage discontinuities within the scope of ISO 16750-2, including profiles for waterfall, cold-crank and load-dump voltage transients.

Supply-Voltage Transient Profiles

Waterfall Test—ISO 16750-2, Section 4.6.2

Fig. 2 describes the supply-voltage profile for the waterfall test to check the reset behavior of the DUT. The test routine is as follows: Decrease the supply voltage 5% from V_{Smin} (to 95% of V_{Smin}) and hold at this voltage for 5 s. Raise the voltage to V_{Smin}, hold for at least 10 s, and perform a functional test. Then decrease the voltage to 90% of V_{Smin}. Continue with steps of 5% of V_{Smin} until the lower value reaches 0 V. Finally, raise the voltage to V_{Smin}.

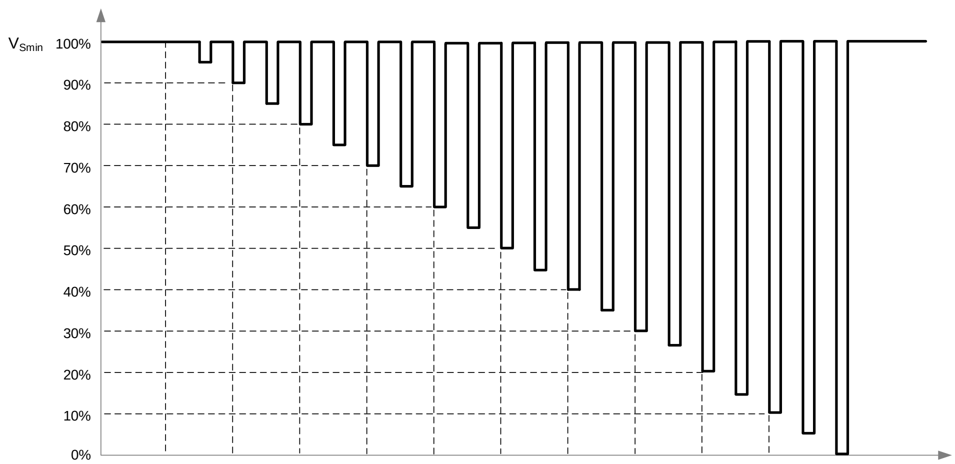

Fig. 2. Supply-voltage profile to verify the correct reset behavior of the DUT at various voltage drops.

Cold And Warm Crank And Start-Stop Profiles—ISO 16750-2, Section 4.6.3

Fig. 3 shows a typical crank profile.[8-10] Table 3 lists the test parameters for starting profiles included in the scope of ISO 16750-2. The level III profile for cold crank of the 12-V system specifies the battery voltage falling to 3 V for 15 ms.

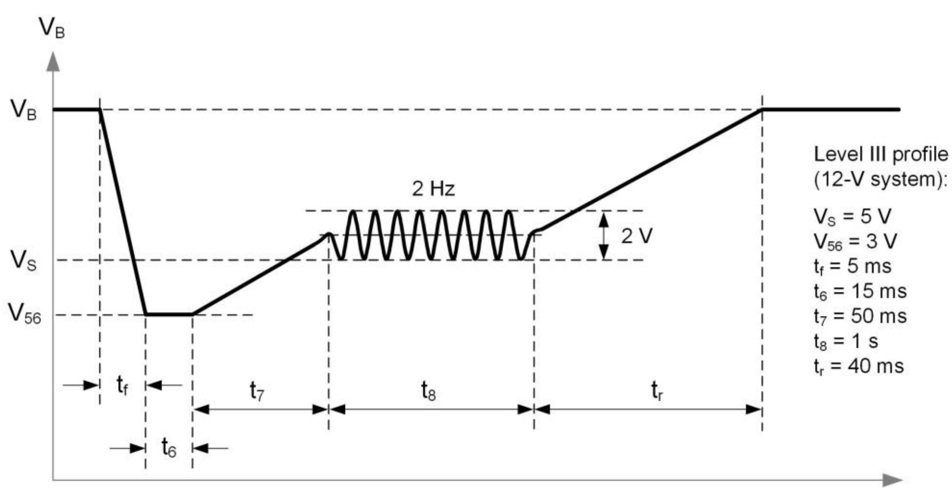

Fig. 3. Starting crank profile described in ISO 16750-2.

Table 3. Test parameters specified for ISO 16750-2 starting crank profiles.

Battery voltage		**12 V**				**24 V**		
Level		**I**	**II**	**III**	**IV**	**I**	**II**	**III**
Voltage (V)	V_{56}	8	4.5	3	6	10	8	6
	V_S	9.5	6.5	5	6.5	20	15	10
Time (ms)	t_f	5	5	5	5	10	10	10
	t_6	15	15	15	15	50	50	50
	t_7	50	50	50	50	50	50	50
	t_8	1,000	10,000	1,000	1,000	1,000	10,000	1,000
	t_r	40	100	100	100	40	100	40

Some OEMs have more complicated voltage profiles defined in their in-house specifications, cited earlier.[5-7]

Load Dump—ISO 16750-2, Section 4.6.4

Fig. 4 shows a schematic of an alternator's three-phase stator windings and the bridge rectifier that converts the stator's ac output to the dc voltage that charges the battery. The alternator's output is controlled by the current in the field winding—the larger the field current, the greater the output current from the alternator. Stator and field windings have large inductances, so changes in field current to provide voltage regulation are inherently low bandwidth.

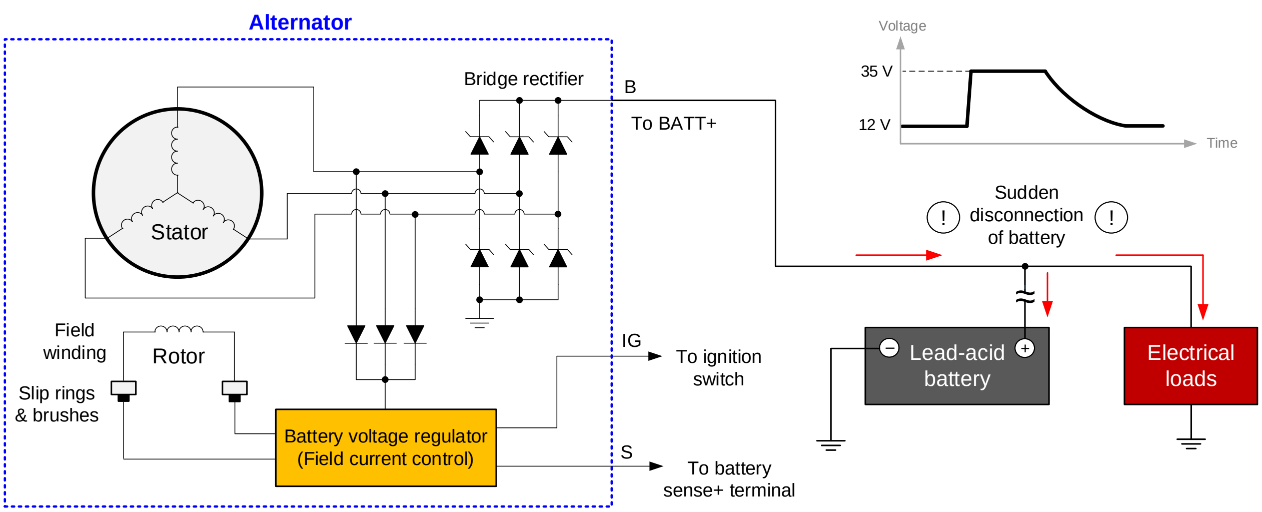

Fig. 4. A six-pack diode bridge rectifies ac voltages from the alternator's three-phase stator windings.

Fig. 4 also depicts the resulting voltage when the battery suddenly disconnects from a loaded alternator while the field winding is still energized. Without the battery to absorb the stator current, the supply rail surges to a high voltage during the unclamped load-dump transient. If the battery charging current is high, the transient overshoot voltage can reach over 100 V, and with low source impedance.

If the alternator is internally clamped (for example, by using avalanche-rated diodes in the bridge rectifier, with the reverse breakdown voltage specified to limit the output voltage), the load-dump transient voltage is clamped to protect downstream electrical loads.

Fig. 5 shows the unclamped and clamped load-dump voltage profiles. These waveforms correspond to the "Test A – Without Centralized Load Dump Protection" and "Test B – With Centralized Load Dump Protection" in ISO 16750-2.

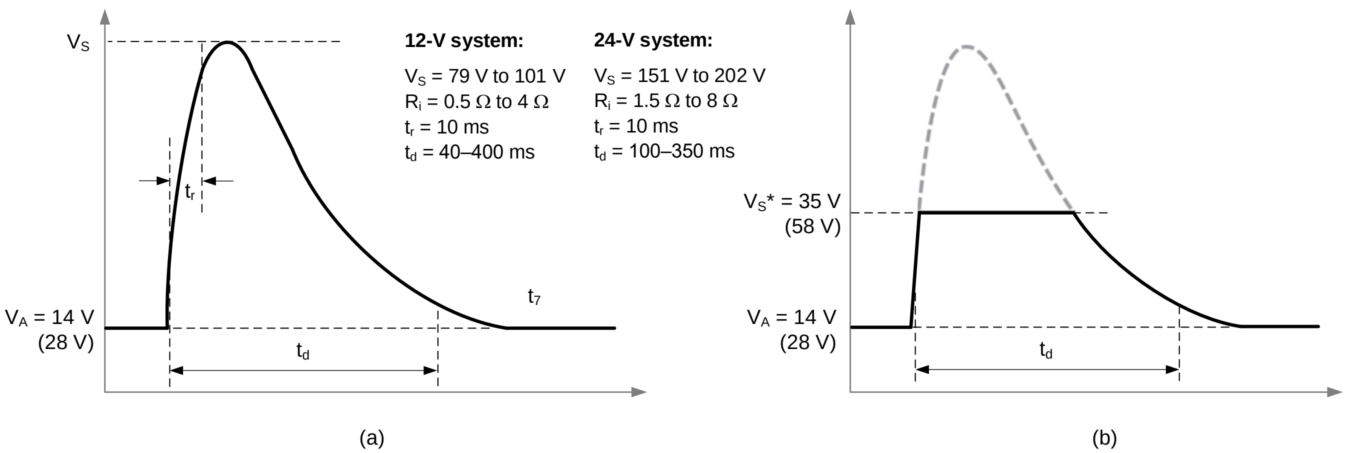

Fig. 5. Unclamped (a) and clamped (b) alternator load-dump profiles as defined in ISO 16750-2.

ISO 7637-2—Electrical Transient Conduction Along Supply Lines

Even though the power-quality tests in ISO 7637-2 were transferred to ISO 16750-2 in 2011, ISO 7637-2 still covers fast transients defined by pulses 1, 2a, 2b, 3a and 3b. Table 4 provides an overview.

Table 4. ISO 7637-2 CI tests in 12-V/24-V automotive battery systems.

ISO 7637-2	**Test**	**Origin of test**	**Test parameters**
Pulse 1	Negative transient sustained by the DUT connected in parallel with an inductive load when the power-line connection is interrupted	Supply-line disconnection with high-current inductive loads (fans; window motors; heating, ventilation and air conditioning)	–150 V (–600 V), 1-µs (3-µs) rise time and 2-ms (1-ms) decay time, 10-Ω (50-Ω) source resistance, 500 pulses
Pulse 2a	Positive transient caused by a current interruption in a device in parallel with the DUT	Current is interrupted to an inductive load in parallel with the electronics being tested	112 V, 1 µs/50 µs, 500 pulses, 2 Ω, 500 pulses
Pulse 2b	Positive transient caused by dc motors operating in reverse	Dc motors act as generators when the ignition is switched off	10 V (20 V), 1 ms/2 s, 0 to 50 mΩ, 10 pulses
Pulse 3a	High transient voltages (dv/dt)—negative transient	Arcing across switches and relays, influenced by the distributed inductance and capacitance of the wiring harness	–220 V (–300 V), 5 ns/150 ns, 50 Ω, 1 hour
Pulse 3b	High dv/dt—positive transient		150 V (300 V), 5 ns/150 ns, 50 Ω, 1 hour

Pulse 1 shown in Fig. 6 illustrates the negative transient seen by the DUT connected in parallel with a high-current inductive load during an interruption of the power-supply connection. Pulse 1 begins with the supply voltage collapsing to 0 V as the supply voltage is removed, followed by a −150-V pulse with rise and decay times of 1 µs and 2 ms, respectively. V_S in Fig. 6 is the amplitude of the negative transient.

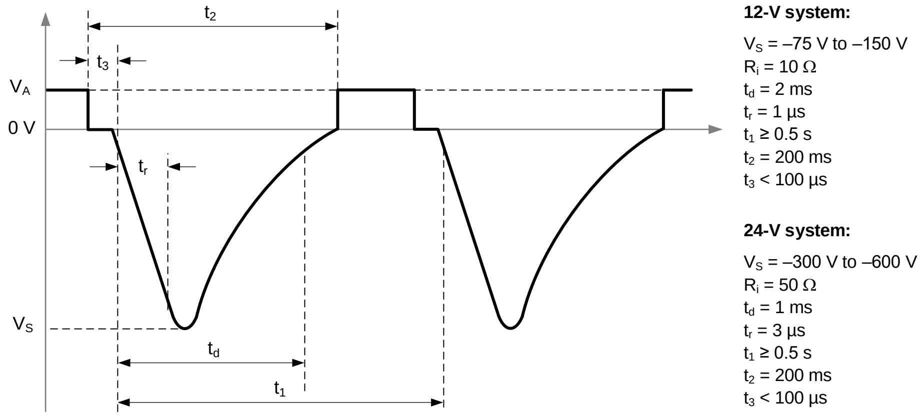

Fig. 6. ISO 7637-2 test pulse 1 waveform.

Pulse 2a shown in Fig. 7a illustrates the voltage overshoot that occurs during an interruption of current to a circuit in parallel with the electronics being tested. If the wiring harness carries high current and a device suddenly stops sinking current, the energy stored in the parasitic inductance of the harness results in a voltage spike. A 2-Ω series resistance limits the energy of this transient.

Meanwhile, pulse 2b in Fig. 7b defines an event that occurs when the driver switches off the ignition and dc motors act as generators. For example, if the heater is running when the driver turns off the car, the blower motor can supply dc power to the system for a short time while it spins down.

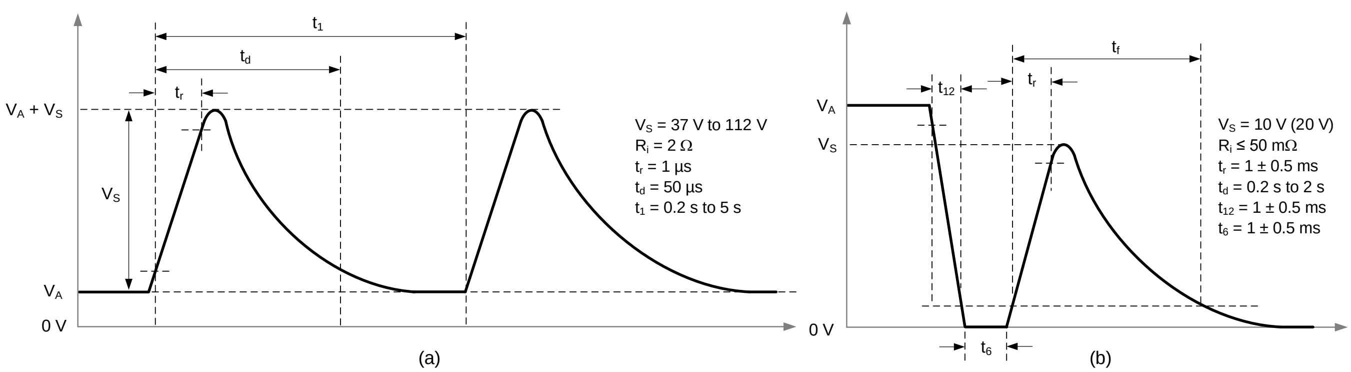

Fig. 7. ISO 7637-2 pulse 2a test waveform (a) and pulse 2b test waveform (b).

Pulses 3a and 3b shown in Fig. 8 detail the negative and positive spikes that may occur as a result of contact arcing and bounce, including arcing across relays, switches and fuses. A 50-Ω series resistance limits the energy according to the specification.

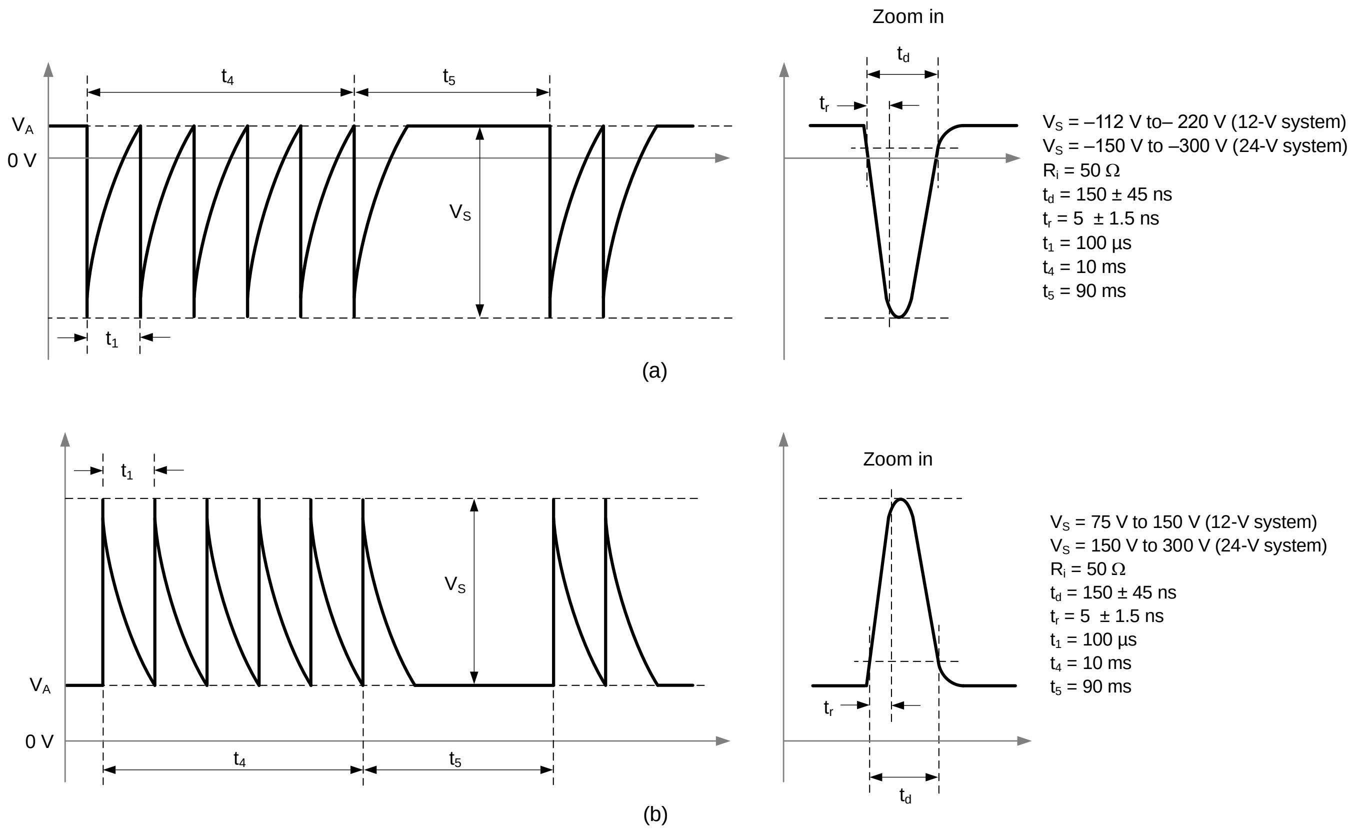

Fig. 8. ISO 7637-2 pulse 3a test waveform (a) and pulse 3b test waveform (b).

ISO 11452—Narrowband RI

ISO 11452 consists of numerous parts under the general title, “Road Vehicles – Component Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy.” Part 1 of ISO 11452 specifies general conditions, defines terms, gives practical guidelines and establishes basic principles for component tests used in the other parts of ISO 11452.

Within this context, Table 5 summarizes the main characteristics of each test referenced in ISO 11452. Note that the wiring harness provides a strong contribution to the coupling path in several tests.

In general, ISO 11452 users should anticipate the appropriate test conditions for the DUT, select applicable parts of ISO 11452, and define a test plan that includes test severity levels and objectives for functional performance status classification.

For example, GMW3097 only references ISO 11452-1, 11452-2, 11452-4 and 11452-8 to include RI, bulk current injection (BCI) and magnetic field immunity tests. Similarly, UNECE Regulation 10 Annex 9 just references any combination (at the manufacturer’s discretion) of ISO 11452-2 for absorber-lined shielded enclosure (ALSE) testing, ISO 11452-3 for transverse electromagnetic (TEM) cell testing, ISO 11452-4 for BCI testing and ISO 11452-5 for stripline testing.

Table 5. ISO 11452 immunity tests and related details.

ISO 11452	Title	Test details	Frequency range	Coupling to	Chamber requirements
-1	Part 1 (2015): General Principles and Terminology	Definitions	–	–	–
-2	Part 2 (2019): ALSE	ALSE method with a specific arrangement	80 MHz to 18 GHz (vertical polarization) 400 MHz to 18 GHz (horizontal polarization)	DUT and wiring harness	ALSE
-3	Part 3 (2016): TEM Cell	Crawford TEM cell	10 kHz to 200 MHz	DUT and wiring harness (or DUT)	Test bench
		Wideband gigahertz TEM cell	10 kHz to 5 GHz		
-4	Part 4 (2020): Harness Excitation Methods	BCI	100 kHz to 400 MHz	Wiring harness	Shielded room
		Tubular wave coupler	400 MHz to 3 GHz		
-5	Part 5 (2002): Stripline	Stripline	10 kHz to 400 MHz	Wiring harness	Shielded room
-7	Part 7 (2003): Direct Radio-Frequency Power Injection	Differential mode excitation to the DUT	250 kHz to 500 MHz	DUT	Bench or shielded room
-8	Part 8 (2015): Immunity to Magnetic Fields	Radiating loop or Helmholtz coil to create H-field disturbance	15 Hz to 150 kHz	DUT	Test bench
-9	Part 9 (2021): Portable Transmitters	EMC disturbance generated by portable transmitters	142 MHz to 6 GHz	DUT and wiring harness	ALSE
-10	Part 10 (2009): Immunity to Conducted Disturbances in the Extended Audio Frequency Range	Conducted voltage test method	–	DUT	Test bench
-11	Part 11 (2010): Reverberation Chamber	Tuned mode method	26 MHz to 5.85 GHz	DUT and wiring harness	Reverb chamber

Of particular importance and widely used is ISO 11452-2, which requires an ALSE for RI testing of vehicle electronic components from an off-vehicle narrowband radiation source.[12] The DUT and wiring harness are subject to a continuous electromagnetic field generated inside the ALSE over a frequency range of 80 MHz to 18 GHz. The setup[6] as shown in Fig. 9 is analogous to that for CISPR 25 radiated emissions, with the antenna positioned at a distance of 1 m and the test performed over the applicable frequency range for each antenna type.

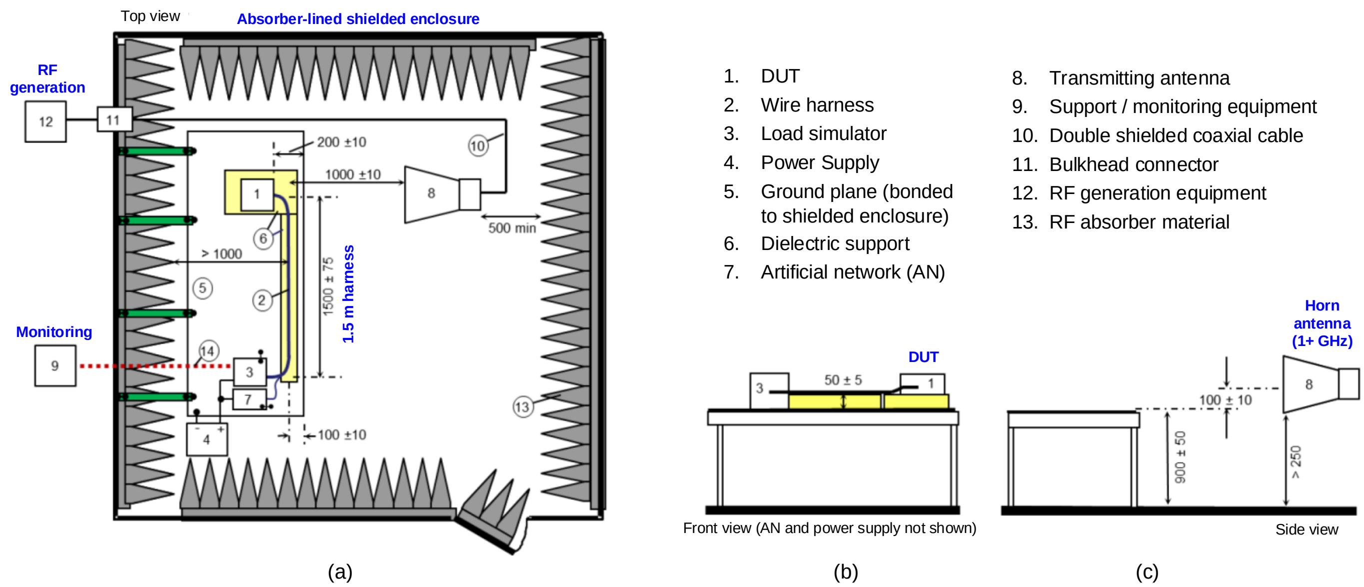

Fig. 9. ISO 11452-2 RI test setup—top view (a), front view (b) and side view (c).

ISO 10605—ESD

Table 6 summarizes the ESD tests according to ISO 10605.[13, 14] The specification uses two different discharge resistors, 2 kΩ and 330 Ω, to simulate different types of ESD events. The 2-kΩ resistor represents a human body discharging directly through skin contact, while 330 Ω simulates human body discharge through a metal object.

The test is also performed at two ESD generator storage capacitances, 150 pF and 330 pF, that represent the capacitance from human body to ground and human body to seat (corresponding to outside and inside the vehicle), respectively. The 330-pF and 330-Ω test provides the highest current amplitude and energy, and is thus the most widely used test condition within the scope of ISO 10605.

Table 6. ISO 10605 automotive ESD tests.

EMC event	**Relevant specification**	**Origin of transient**	**Test details**
ESD	ISO 10605 (partly derived from the IEC 61000-4-2 commercial standard) applies to ESAs and complete vehicles	ESD during assembly or caused by service staff or occupants; the test simulates a discharge from the human body inside or outside the vehicle	2- to 15-kV contact discharge 2- to 25-kV air-gap discharge 3 pulses minimum

A discharge with 330 Ω and 330 pF has the highest energy of any of the tests, indicated by having the largest area under the current vs. time waveform. In comparison to IEC 61000-4-2, which has a lower capacitance of 150 pF and 330 Ω, ISO 10605 at 330 pF and 330 Ω has a longer period of energy dissipation. Consequently, the

DUT stress with this specific ISO 10605 test is significantly higher than that from IEC 61000-4-2, making it a more intensive test.

Summary

A primary objective of this article is to emphasize the importance of understanding EMC requirements early in an automotive design. Automotive off-battery power supplies are subject to formidable transients during normal operation, and such transients can readily destroy exposed onboard electronics. Automotive manufacturers have combined efforts with standards bodies to develop specifications such as ISO 7637-2 and ISO 16750-2, which describe the possible transient events and specify test methods to simulate them.

Part 2 of this article series will describe the design of an off-battery dc-dc solution, including a front-end circuit for protecting electronics connected to the automotive 12-V battery.

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About The Author

Timothy Hegarty is a senior member of technical staff (SMTS) in the Buck Switching Regulators business unit at Texas Instruments. With over 25 years of power management engineering experience, he has written numerous conference papers, articles, seminars, white papers, application notes and blogs.

Tim's current focus is on enabling technologies for high-frequency, low-EMI, isolated and nonisolated regulators with wide input voltage range, targeting industrial, communications and automotive applications in particular. He is a senior member of the IEEE and a member of the IEEE Power Electronics, Industrial Applications and EMC Societies.

For more information on EMI, see How2Power's Power Supply EMI Anthology. Also see the How2Power's Design Guide, locate the Design Area category and select "EMI and EMC".