

The role of grounding in automotive EMC

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Abstract. We discuss grounding issues specific to automotive applications. We review the components of a typical automotive ground system, their intended functions, and known limitations. Some sources of automotive emissions are identified and the role of ground in mitigating these emissions is discussed.

INTRODUCTION

Automobiles, particularly those powered by spark-ignited engines, present a number of EMC challenges. In addition to ensuring compliance with various international, state and local EMC standards, it is necessary to achieve mutual compatibility among arc generating devices (spark plugs and relay contacts), electrical power generating equipment, digital logic at tens of MHz and higher, high-current inductive loads (e.g., motors, solenoids, primary ignition system), and precision analog sensors. Furthermore, the EMC engineer must address the performance of passenger conveniences including the entertainment radio, cellular phones, GPS, collision detection sensors (radars and laser radars), and other more advanced functions proposed for intelligent vehicles.

Although the secondary ignition system has long been recognized as a significant source of radiated emissions, many other components in modern vehicles produce conducted emissions at 100 kHz and above. The electrical equipment in vehicles is increasing both in quantity and sophistication. Superimposed on these technical challenges is a need to meet high consumer expectations of quality in a cost competitive environment.

Conductors referred to as “ground” often (intentionally or unintentionally) perform more than one function in electronic systems, but the role of ground is somewhat more diverse in vehicles. The term is commonly applied to a variety of vehicle conductors, which function as

- a current return path,
- an equi-potential conducting surface that provides voltage reference level for analog sensors and digital logic,
- a counterpoise for AM and FM antennas,
- shield conductors used for RF current bypass, and

- electrostatic charge drains.

In this paper we review issues that affect “grounding” in automotive systems, and we present examples that illustrate some key concerns.

THE AUTOMOTIVE GROUND SYSTEM

Overview

The automotive electrical system is powered by an alternator connected in parallel with the storage battery (see Figure 1). Alternator voltage regulation is performed by a component located within the alternator or in an external module (e.g., the engine controller). The alternator and the battery are both possible sources of current for a given load. When the engine is running the alternator supplies current for most DC loads, but the alternator's internal inductance is too large to permit it to supply rapidly switched currents. The latter currents are drawn from the battery. Because of this configuration, the current return path is somewhat ambiguous.

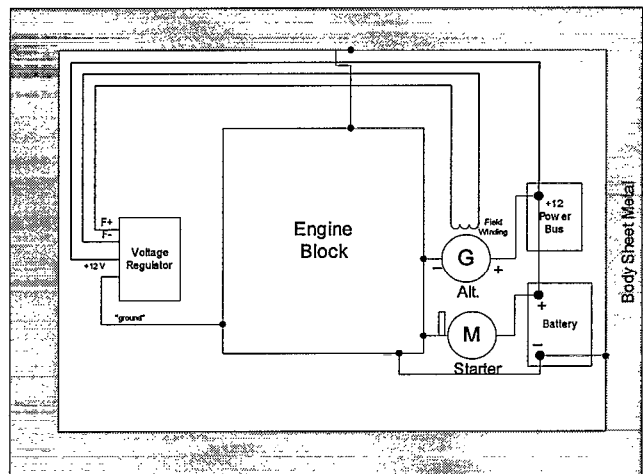


Figure 1. Typical configuration for vehicle battery and charging system.

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The starter motor introduces additional constraints. Correct function of the starter is a principal consideration in automotive grounding. The current return path for this device must exhibit low DC resistance from battery negative to the starter motor ground (typically the engine block) to ensure starter function in cold weather. The locations of starter motor and battery may lead to unfavorable loop geometries for this conductor.

Components

A number of components are deliberately used for grounds on vehicles. These include body sheet metal, the engine block, wiring, and the battery.

Body sheet metal (BSM)

Although there is a trend toward composite or plastic body panels in vehicles, the majority of vehicle bodies still have significant metal content. Because of its size, shape, and convenient location (i.e., adjacent to most electrical components), BSM offers unique opportunities for current return, potential referencing, shielding, and noise reduction. A goal of good vehicle ground design is to maintain the unique benefits of BSM to the extent possible.

The body's large surface area and convoluted shape provide a significant amount of self-capacitance, and it has been found that BSM is an effective sink for high-frequency noise currents of small amplitude. Doing so, however, risks common impedance coupling, particularly when the current must pass through body panel joints. In addition, indiscriminate use of BSM as a universal current return path can eliminate its beneficial features and create a significant source of radiated emissions. An example is shown in Figure 2, where we present measurements of surface electric field on two vehicles. In the first vehicle BSM was inadvertently used as a return for some ignition currents. The propagation of these currents along the fender of the vehicle produced noise in the entertainment radio. The second vehicle used identical components, but the component mounting was such that the current return path avoided BSM near the fender.

BSM can be used for low-frequency capacitive shielding. At kHz frequencies and above, BSM offers modest electromagnetic shielding of the engine compartment as a result of its skin depth. It is also the primary conductor through which the vehicle is shielded from lighting, human-generated ESD events, and external sources. Reliable electrical integrity of this shield, however, is not ensured by common methods of vehicle body construction. Metal panels may be joined with spot welds or bolted together with intervening layers of nonconductive corrosion inhibitor, or with nonconductive paints. Ideally, sheet metal panels should be electrically bonded, and movable panels (hood and door) connected with auxiliary conductors (ground straps). BSM should be tied to battery minus through a robust low-impedance bond.

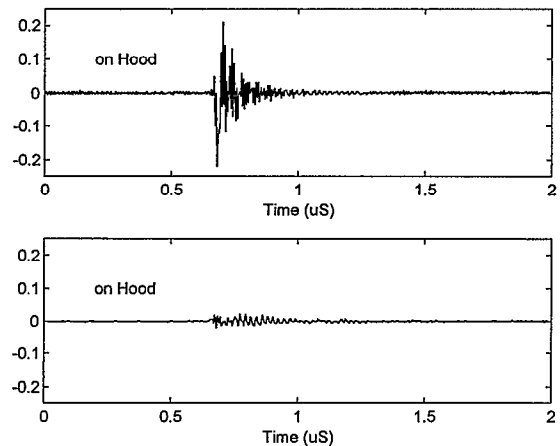


Figure 2. Surface electric fields on body sheet metal for two vehicles.

Engine block and cylinder heads

A variety of electrical signals flow in the engine block and cylinder heads. In addition to their potential for conducted coupling, some signals can create a voltage between the engine assembly and body sheet metal via return lead inductance. This voltage can produce radiation or capacitive coupling to under-hood electronics.

The engine and cylinder heads are in intimate physical contact and joined by a number of large diameter bolts, but the electrical properties of these connections are often poor. Head gasket materials are often electrically insulating and coatings used on head bolts can be poor conductors. Joints from the block to other engine components are (including the alternator housing, valve covers, and throttle bodies) are also uncontrolled and subject to change during engine servicing.

Wiring

The sizes of the engine and vehicle components are sufficient to create unavoidable ground impedances at high frequencies. Because the distances between these components are large (on the order of one meter), the problem of inductance in the current return path is difficult to eliminate. With typical wiring inductances of a few tens of nH/inch [1], it follows that ground inductances on the order of 1 μ H cannot be avoided for many vehicle components. Currents of a few Amperes or more (common in vehicle systems) with frequency content above 100 kHz can produce unacceptable voltage drops in a current return path.

Battery

In addition to its intended function as an electrical energy storage device, the battery performs a number of noise suppression tasks. Battery electrical characteristics are highly nonlinear functions of frequency, charge state, and load current. At low frequencies a lead-acid battery exhibits a

capacitive reactance of 1-2 F per 100 ampere-hour (Ah) [2]. When placed in parallel with the alternator, this reactance tends to reduce low-frequency noise components produced by the vehicle charging system.

At higher frequencies the response of the battery is more complex. The capacitance of a typical lead-acid vehicle battery of roughly 100 Ah capacity is shown in Figures 3 and 4. In the regime from 25 kHz to 250 kHz the battery has a capacitance (several tens of nF), which is roughly constant with frequency. Variations of an order of magnitude in the effective capacitance have been observed depending on the battery's state of charge and size. At higher frequencies the battery reactance is best described by a series LC circuit that includes lead inductance. In this regime, series resonance is common as shown in Figure 4 for frequencies above 1 MHz. Because of this behavior, the battery should not be relied upon to provide RF noise suppression in the AM broadcast band and above.

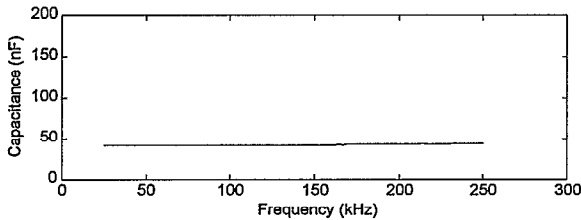


Figure 3. Capacitance of a lead-acid automotive battery over the frequency range 25 kHz to 250 kHz.

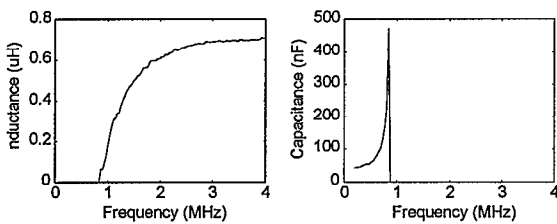


Figure 4. Equivalent capacitance and inductance of a lead-acid automotive battery with attached leads over the frequency range 200 kHz to 4 MHz. The net impedance passes through a series resonance near 1 MHz.

AUTOMOTIVE EMC CONCERNS

As noted above, vehicles contain a variety of emitters and susceptible components. In this section we discuss those components that are unique to the automotive environment. Characteristics of more common automotive components, e.g., positioning motors, rapidly switched high-current DC loads, and analog sensors, are not considered here in the interest of brevity. Some discussion of these topics appears in [3].

Ignition

Emissions by vehicle primary and secondary ignition circuits are often problematic. These two circuits involve significantly different waveforms and, while they are coupled through the ignition coil, they are treated separately here. Because of the trend toward distributor-less systems and coil-on-plug designs, we omit consideration of distributors and spark plug wires.

Primary Ignition Circuit

The primary ignition circuit involves a current supply (the battery or alternator), the ignition coil and a triggering device (typically the engine control module). A common configuration for this circuit is shown in Figure 5.

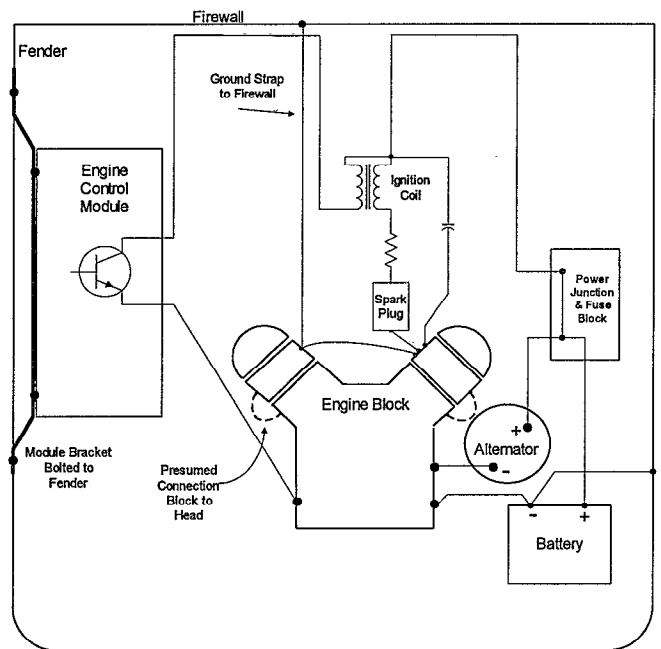


Figure 5. Typical primary ignition system.

The principal EMC concern for this circuit relates to the trailing edge of the coil current waveform, drawn as a ramp in Figure 5. The falling edge of the coil current and the voltage across the coil are shown in Figure 6. This portion of the waveform contains significant high-frequency energy (at 100 kHz and above), that will be affected by inductance in the ground return wiring. As shown in Figure 5, the return path includes the engine controller and the engine block. This path can comprise a ground inductance on the order of 1 μ H, which may cause the engine controller and engine block to have potentials of several Volts with respect to battery negative.

The problem can be partially mitigated by reducing the loop areas and positioning the components to shorten the wiring as much as possible. In addition, the return path for these

currents to battery minus should not include any conductors used as potential references nor BSM as noted previously.

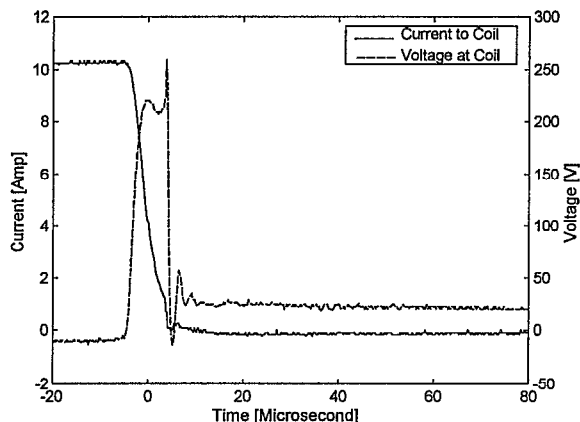


Figure 6. Primary ignition voltage and current.

Secondary Ignition Circuit

The secondary ignition system involves the ignition coil, spark plug, cylinder heads, and other conductors as shown in Figure 7. The secondary ignition signal is unique among waveforms generated by the vehicle, because its spectrum extends to roughly 1 GHz. This feature makes it particularly prone to radiated emissions, but conducted coupling to other parts of the engine is also possible.

The mechanism by which the secondary ignition circuit generates high-frequency emissions is illustrated in Figures 7 and 8. The battery supplies DC power to the primary windings of the ignition coil. Primary and secondary windings are arranged in an auto-transformer configuration. Electronic switching in the engine controller opens the primary side of the windings over a time period on the order of 10 μ s (cf. Figure 6). The primary side voltage is amplified by the coil turns ratio (on the order of 100), producing a secondary voltage of several tens of kV. A RF suppression capacitor C_{RF} is placed between the high side of the ignition coil and the cylinder head. The inductance of the primary windings is a few mH, and a resistance R_c (several Ohms) is placed in series with the coil output.

The RF characteristics of the spark plug can be modeled by (1) an equivalent arc impedance R_{arc} , which describes the nonlinear, time-varying flow of current through the spark gap and (2) a coaxial capacitor C_p formed by the threaded outer metal case of the plug and the inner conducting core. The spark gap is essentially nonconducting until arc discharge is initiated, and we represent this initiation by a switch. After initiation, the capacitor C_p discharges rapidly through the gap.

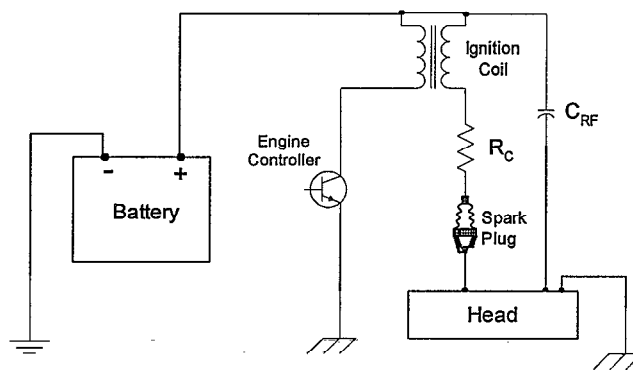


Figure 7. Simplified view of ignition system.

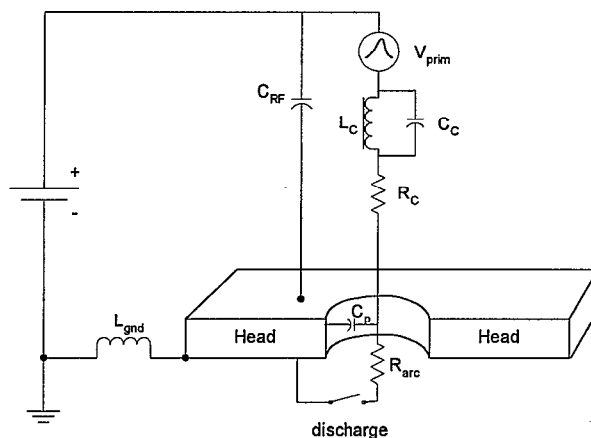


Figure 8. Action of the secondary ignition system.

An equivalent circuit for the secondary side including a spark plug model is shown in Figure 8. There, the voltage induced by the primary side is represented by an equivalent series voltage source. The current return path to the battery is represented by an equivalent inductance, although at sufficiently high frequencies capacitance and radiative losses may also play a role. Parasitic capacitance across the windings is represented by C_c . In this figure we do not show coupling from the secondary side back into the primary side wiring via capacitance in the ignition coil. This form of coupling can both increase the potential for radiation and the opportunity for conducted coupling into electronic systems.

Entertainment Radio

The entertainment radio is a shielded high-gain amplifier connected to a monopole antenna. The radio is (by design) susceptible to noise in the kHz and MHz range, a variety of which is produced by the vehicle's electrical and mechanical systems.

Typical radio wiring is shown in Figure 9. A coaxial line connects the radio to the receiver. The coax outer conductor forms a continuous shield between the fender (antenna

counterpoise) and the receiver housing (shield). The vehicle designer does not typically know the connections made within the receiver housing. It is reasonable to assume, however, that consistent with good design practice the “ground” wire is tied to the case and is bypassed at the case penetration. For the purposes of this discussion, we will consider a receiver housing that is also connected to body sheet metal via a ground strap. Power and ground are supplied to the receiver as well. Typically, unshielded apertures for cooling penetrate the radio housing and power supply leads.

The entertainment radio system may employ several grounds. A connection from coax outer shield to BSM is required to provide a counterpoise for the monopole antenna. A second connection (coax to radio housing) is necessary to divert noise currents from the coax outer surface to the radio housing and to provide a return path for the antenna signal. If a connection from radio housing to body sheet metal is absent, the large metal radio housing will couple capacitively to body sheet metal, and noise potentials present in body sheet metal will then be impressed on the receiver’s reference voltage. If the coax outer conductor does not make good contact with the receiver and radio housing, noise currents will be coupled into the receiver. Finally, if the receiver is not grounded to the radio housing, noise potentials present on the radio housing will couple capacitively to the receiver.

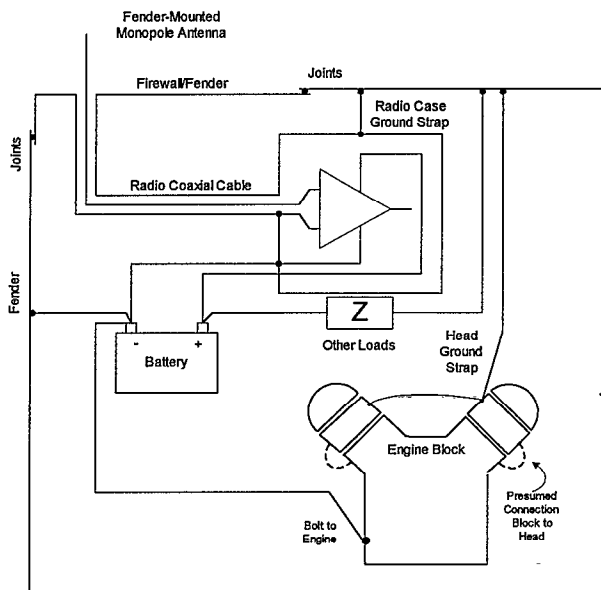


Figure 9. Entertainment radio grounding.

Charging System

In addition to its previously described role as a current source and return point, several sources of EMI are produced by the charging system.

Charging System Wiring

A conventional charging system design was shown in Figure 1. The currents are returned to the engine assembly and/or battery minus through a large-diameter low-resistance starter-return connection between the engine block and battery minus. Two problems arise in trying to develop a good ground system for this design. First, because of the size and placement of battery and starter, the return path involves long leads, which produce a large ground inductance. Second, the resistance of the engine assembly is variable, since it comprises a number of separate structural components (block, heads, manifolds, and alternator mounting bracket), and the electrical properties of their connections are not controlled during assembly or maintenance.

Charging System Components.

Noise produced by the alternator and voltage regulator should also be addressed in ground design. This noise has several sources, including (1) brush noise due to intermittent contact quality at the alternator slip rings, (2) harmonic generation during AC rectification, (3) diode noise impulses produced when the rectification diodes are reverse-biased, and (4) high-frequency content on the voltage regulator lines, produced during pulse-width modulation of the field windings. The alternator drive belt is also a source of noise, because of static charge motion caused by friction and mechanical motion of the belt. This minor noise source is superimposed on other far larger capacitive and radiated signals produced by the engine, and will not be discussed further.

The standard method of mitigating alternator noise is to exploit the capacitance present in the battery as discussed above. As shown in Figure 1, the battery’s low-frequency capacitance is placed in parallel across the alternator. We noted previously that this technique is acceptable for low-frequency noise, but it can fail at high frequencies because of the battery’s complex frequency response and the large wiring inductance. To improve high-frequency performance the noise should be shunted to ground as close to the alternator housing as possible. The housing should be connected to battery negative by a low-impedance path. Care must be taken to minimize the lead lengths of this connection and to minimize its coupling to other circuits.

Fluid Distribution Systems

The mechanical action of pumping and the subsequent flow of fluid through lines and filters can cause charge separation in fluids. As a result, fluid system components can become electrically charged. When the charge reaches a critical level, an electrostatic discharge occurs, leading to erosion or pinhole leaks in lines and tanks. The accumulation of charge can also be a source of noise to nearby radio receivers. Although the phenomena can occur for any of the fluids used in automotive applications, charge separation is related to fluid velocity. For this reason the engine cooling, air conditioning, and fuel systems are of greatest concern. The

high conductivity of engine coolant reduces its potential for charge separation and, instead, its components (radiator, heater core, etc.) should be viewed as electrical extensions of the engine block. Charge separation is particularly serious for fuel systems, because of the potential for fire or explosion.

Although it has been known for many years that fluid flow could produce charged lines, the process is not very well understood. Some information on the topic has been compiled in SAE J1645 [4] and in the experiences of the petroleum industry and spacecraft designers. In general, it has been observed that certain devices are charge separators. These devices include devices that add energy such as pumps, and components with large surface areas such as filters and heat exchangers. Separated charges tend to diffuse onto the surface of an insulated line. This charged surface quickly attracts an opposite compensating charge, forming a charge double layer. Charges accumulate at reservoirs, including accumulators and tanks. All such components should be tied to adjacent ground conductors.

Non-Electrical Components

A number of non-electrical vehicle components can be effective noise radiators by virtue of their size, shape, and mounting characteristics. Examples of these components include the engine block (discussed previously) and cylinder heads, radiators and heater core assemblies, and exhaust pipes. Coupling of noise signals to these components can occur via conductive, capacitive, inductive, or radiative processes. In this section we describe the use of ground and cable routing to reduce radiation from these components.

Radiator and Heater Core Assemblies

In many vehicles the radiator is secured to the body with non-conductive rubber bushings and, as a result, the radiator may be electrically isolated from a potential reference. A similar situation exists for the passenger-compartment heater core. Under these conditions, they comprise floating metal, which will tend to enhance capacitively coupled noise. This interference mechanism is particularly troublesome for the heater core, which is typically located close to the

entertainment radio. To suppress these noise sources, both radiator and heater core should be grounded to body sheet metal at a minimum of one point. Growing use of aluminum radiators causes additional problems. The metals used to make these connections must be selected to minimize the potential for electrochemical corrosion at the contacts.

Exhaust Pipes

The exhaust pipes, which are bolted to the heads via the exhaust manifolds, function as monopole antennas driven against the engine as a counterpoise. The drive-train can produce similar radiation. Conducting straps should be used to short these radiators to BSM.

CONCLUDING REMARKS

In this paper we have reviewed the use of ground in automotive applications. Ground design in these applications must address a diverse variety of electronic and electromechanical devices, which must operate in close proximity. The number and sophistication of automotive electronic driver conveniences is also increasing rapidly. EMC engineers are challenged to meet these requirements in an environment that is extremely sensitive to cost, product quality, and schedule

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