Electromagnetic compatibility performance of large area flexible printed circuit automotive harness

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Abstract: Electrical interconnection is increasingly important to the functionality of modern vehicles. At the same time the drive within the industry to reduce costs and improve fuel efficiency requires the reduction of the weight of vehicles wherever possible. It is in this context that the possibility of using large-area flexible printed circuits (FPCs) in place of wiring harnesses is receiving strong interest from manufacturers. An FPC harness offers a substantial weight reduction over wire, improved reliability and quality control, and enhanced functionality. Since good electromagnetic compatibility (EMC) design and performance is necessary for the safe and proper functioning of a vehicle, it is important to know if the EMC performance of a vehicle is likely to be compromised by the incorporation of an FPC harness. This question is addressed in this work by comparing the performance of wire and FPC structures in a standard EMC test. The cost implications of anti-interference measures for mass production of FPC harnesses are also assessed. It is found that relatively cheap and simple to implement track structures can significantly reduce the amount of coupling to a large-area FPC automotive harness from an external electromagnetic field.

Keywords: wire harness, large-area flexible printed circuit, FPC, electromagnetic compatibility, EMC, RFI, twisted pair

NOTATION

F	frequency
δ	skin depth
σ_r	electrical conductivity relative to copper

1 INTRODUCTION

1.1 Large area flexible printed circuit automotive harness

Electrical interconnection is increasingly important to the functionality of modern vehicles, in particular for incorporation of intelligent control modules. It has been estimated that the average total length of wiring in a modern car is more than 1800 m [**1**]. At the same time the drive within the industry to reduce costs and improve fuel efficiency requires the reduction of the weight of vehicles wherever possible. It is in this context that the possibility of using large area flexible printed circuits (FPCs) in place of wiring harnesses is receiving strong interest from manufacturers [**1**].

An FPC harness offers a substantial weight reduction over wire, due to the smaller mass of copper and dielectric materials required for a given current capacity. There are other benefits to be gained. Manufacturability is improved. Construction of round wire harness is labour intensive, but low-cost FPCs are produced by an inherently mass-production, reel-to-reel process, having associated labour cost reduction and quality control advantages. Reliability is improved because of a reduction in the number of connectors required. In addition, connectorization of FPCs is more straightforward than for wire, since wires have to be individually arranged in the connector, whereas FPC connector systems automatically locate the circuit correctly in the connector housing. Finally, there is the prospect of enhancing functionality

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of FPC harnesses through incorporation of surface-mounted active devices on the flexible interconnection media.

Relatively small, low-cost FPCs have already seen extensive use in car manufacture, most notably in the instrument cluster [**1**, **2**]. It is proposed that FPCs of large enough size and composed of cheap laminate materials can replace round wire over substantial portions of the vehicle. A typical instrument cluster circuit is 500 mm × 250 mm [**2**]. The circuits required as harness substitutes are potentially much larger, with up to 1500 mm × 750 mm being considered for cockpit applications. Although a typical maximum size capability of a current reel-to-reel FPC manufacturer is 500 mm × 750 mm, the construction of such large-area FPCs is achievable using current manufacturing processes. Machines with the required size capability are either already available or would be straightforward developments of existing designs [**2**].

The main barrier to development of large area automotive FPC is therefore not technical, but rather the costs and investment risk of upgrading the panel size capability of existing FPC manufacturers. Other considerations are the unit cost of an FPC harness compared to a wire harness, the absence of standards and reliability data for FPC laminate materials in an automotive environment, and confidence in the capability of FPC automotive harnesses to support both the existing and near future functionalities supported by wire harnesses. The costs [**2**] and materials [**3**] issues have been addressed in our previous work, as has the functional ability of FPC to handle high-speed digital transmission of data [**4**].

1.2 Large area FPC harness and EMC

This paper concerns the electromagnetic compatibility (EMC) or RF interference noise rejection function of FPC harness, as compared to wire harness. Good EMC design and performance is necessary for the safe and proper functioning of a vehicle. It is therefore important to know if the EMC performance of a vehicle is likely to be compromised by the incorporation of an FPC harness. A wiring harness acts as an aerial to couple RF energy into or out of devices interconnected by the harness [**5**]. An FPC harness will act in the same way. The amount of RF noise coupled into a circuit depends more strongly on geometry; i.e. lengths and layout of current paths, than on whether the current is carried by a wire or an FPC track. However, protection against RF interference for specific circuits in a wire harness can be achieved by the use of a twisted wire pair or of shielding. The major question addressed by this work is whether similar levels of protection can be achieved with suitable structures on an FPC harness. The approach taken is comparative. The degree of coupling between radiated electromagnetic fields and both wires and FPC circuits are measured and compared in a standard test.

2 BACKGROUND

2.1 Manufacturing considerations for large-area FPC automotive harness

It is important to consider the cost and manufacturing implications of any EMC ameliorative measures incorporated into the design of a large-area automotive FPC harness. A detailed analysis of the implications of the design of FPC harnesses for FPC manufacturers, automotive original equipment manufacturers (OEMs), and other stakeholders is given in Cottrill *et al.* [**2**]. For current automotive FPC production reel-to-reel processing is favoured because of the high volume and low cost [**2**]. Most circuits are made by a subtractive method starting with a laminate of copper foil and a low-cost base dielectric film, such as polyester. An etch-resist ink is screen printed on to the laminate prior to etching. A protective coverlay film or ink is then applied to the etched laminate. A conductive screening foil can also be applied. Single or double-sided circuits can be made and a small number of side-to-side interconnections achieved by mechanical means, such as crimping. The reel-to reel processing means that it is difficult to incorporate time-consuming processing stages. In particular through-hole plating requires 30–40 min just for the initial electroless deposition of the copper seed layer. Silver-loaded conductive ink can be used to make bridges, but is expensive and has a surface conductivity a tenth of that of copper foil of the normal thickness of 35 μm.

2.2 Likely EMC performance of large-area FPC automotive harness

There are reasons to think that the EMC performance of large-area FPC harnesses may be superior to equivalent wire harnesses. Sources of RF interference are external and can therefore vary with the location of the car, and internal, including cross-talk effects between circuits in the harness. The position of any individual wire, relative to other wires, varies from wire harness to wire harness. The degree of cross-talk and degree of coupling to external fields can therefore vary from harness to harness [**6**]. By contrast the routing of tracks on an FPC is specified in the design and the EMC variability between FPC harness units will be much less. Additionally, EMC performance of an FPC harness can be optimized by routing tracks to reduce cross-talk between noise-generating circuits and noise-sensitive circuits. The amount of cross-talk between any two circuits on an FPC can be predicted [**7**]. This gives an improved ability to estimate EMC performance at the design stage of a vehicle and fits in with the industry trend towards virtual vehicle testing [**8**].

Further improvement in reducing coupling between an automotive FPC harness and external fields would involve protecting sensitive tracks in some manner. There are two approaches: using track structures designed to mimic the function of the twist in a wire twisted pair and adding shielding. Both approaches are analogues to measures taken with wire harness, i.e. shielding and wire-twisted pair. The physics of these approaches are treated in section 2.5.

2.3 Automotive EMC testing

In order to prove that a vehicle's electronic systems function in the presence of external RF interference, whole vehicle tests are carried out at the physical prototype testing stage in a screened testing chamber [**9**]. The vehicle is exposed to electromagnetic fields in the frequency range 10 kHz to 10 GHz or more, and at field strengths up to 200 V/m. The whole vehicle tests have the disadvantage that they cannot be carried out until the prototype is at an advanced stage of development, by which time design changes to solve EMC problems are costly. Vehicle component EMC tests allow individual components to be tested at an earlier stage of development. The component under test and the wiring attached to the component are irradiated in a suitable fixture [**10**]. The operation of the component at given field strengths is tested and classified according to the severity of any failure and the consequences for the functioning of the vehicle. The approach taken in this work was to select an automotive system and to compare its performance in a vehicle component EMC test when wire and FPC are used for interconnection. The automotive system chosen was the bus of a high-speed controller area network (CAN).

2.4 Controller area network (CAN)

CAN is an example of an automotive multiplexed network, a system that allows transmission of digital information between different controller modules attached to a common bus, thereby reducing the number of point-to-point connections required in the harness [**11**]. The Society of Automotive Engineers (SAE) has defined three categories of network denominated, in order of increasing transmission rate, as Classes A, B, and C [**12**]. High-speed CAN is a Class C network, capable of operating at 125 kbs^{-1} to 1 Mbs^{-1} and supports, for example, control and monitoring of the powertrain and anti-lock braking. Protection of the CAN bus from RF interference is therefore extremely important [**13**].

The topology of a CAN network is illustrated in Fig. 1. The bus consists of a pair of wires, CAN_H and CAN_L, terminated at both ends by 120 Ω resistors. CAN nodes are connected between the lines in parallel with the termination resistors. Neither bus line is earthed and a differential signalling scheme is used whereby a bit consists of a voltage difference appearing between the lines. This balanced circuit configuration is noise-robust because it allows rejection of common mode noise at

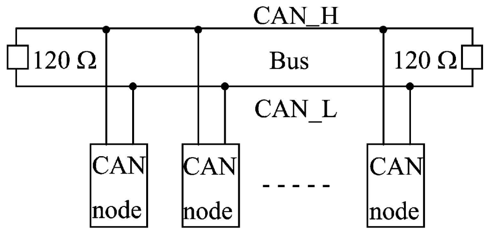

Fig. 1 CAN network topology

the CAN node inputs. Common mode noise is a noise voltage appearing simultaneously on both lines of the bus. The bus for CAN is usually a shielded or unshielded twisted wire pair. The use of the twist provides extra immunity to electromagnetic interference (EMI), the physical reasons for which are treated below.

2.5 Physics of twisted wire pair and shielding

Paul [**14**] has treated the effect of wire twist on cross-talk between adjacent circuits at low frequencies. Consider a CAN bus consisting of an unshielded twisted wire pair adjacent to a single wire carrying a noise-generating current, as illustrated in Fig. 2. Magnetic flux created by the generator wire current threads the loops of the twisted pair, creating an induced electromagnetic field in each loop. However, adjacent loops are of opposite polarity so that the emfs tend to cancel. The twist therefore reduces the degree of magnetic field or inductive coupling. Paul also shows that the electric field or capacitive coupling between the generator wire and a balanced circuit is ideally eliminated. At higher frequency the twist helps ensure the current return path is through the twisted pair and not via some parasitic path, e.g. through earth, because of the mutual inductance of the wire pair [**15**]. This is desirable because the area enclosed by the current path is made as small as possible, again reducing the degree of electromagnetic coupling to the circuit.

Several patents exist [**16–20**] for printed circuit structures claiming to emulate the effect of a wire twist. These make use of plated through-holes (PTHs) or wire bridges to interweave the current paths of the signal and return. An example is shown in Fig. 3. The use of PTH or bridges over a large area has cost implications, because of the difficulty of integrating the relatively slow PTH processes into a reel-to-reel FPC line.

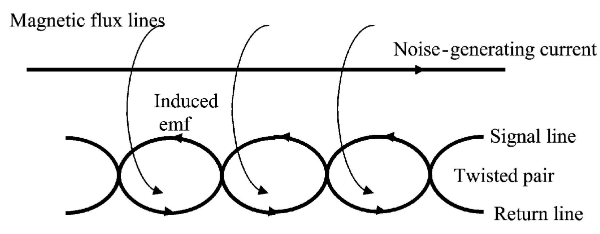

Fig. 2 Magnetic field coupling to a twisted wire pair of a noise-generating current on an adjacent wire

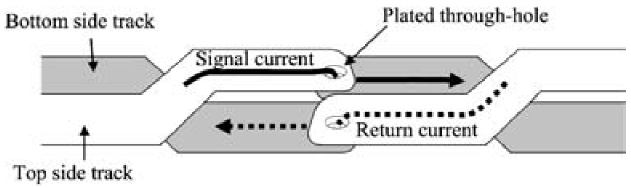

Fig. 3 FPC track pattern intended to emulate the effect of a twisted wire pair

The shield on a shielded cable reduces coupling of an electric field to the signal wire. The shielding effect arises because of currents induced in the shield by the interfering field. An AC electric field incident on a solid conductive shield is partly reflected and partly transmitted. The amount of the field transmitted is dependent on the thickness of the shield and its conductivity. The thicker the shield and the higher the conductivity the greater the shielding effectiveness. The shield thickness should be several times greater than the skin depth δ, the layer within which most of the induced shield current flows. The skin depth in m is given by $\delta = 0.0661 (F\sigma_r)^{-0.5}$, where F is the frequency, σ_r is the conductivity relative to copper, and the relative permeability is taken to be unity. For typical aluminium the skin depth is 15 μm at 30 MHz [**15**]. Shielding of selected areas of an FPC can be achieved by applying foils to the top and bottom of the panel. However, the shielding effectiveness will be reduced by comparison with a cable shield. This is because the screen on a cable provides a 360° wrap of the signal wire, but on an FPC the top and bottom shields are separated by the thickness of the FPC laminate, forming an aperture in the shielding. Apertures in a shield reduce the screening effectiveness by a factor which increases with decreasing wavelength, until the shielding effectiveness is reduced to zero when the wavelength is much shorter than the longest aperture dimension [**15**]. The shielding effect of top and bottom shields on an FPC will therefore be most effective at low interference frequencies and completely ineffective at very high frequency.

2.6 Automotive component EMC tests and choice of test

In this work we are interested in the comparative degree of coupling of wire and FPC track structures to radiated electromagnetic fields. It would be desirable to use standard automotive component EMC tests to make the measurements since these are tests with which engineers in the target market for this technology are already familiar. The SAE defines several standards for automotive component EMC tests in which coupling of radiated electromagnetic fields to the wire harness plays a role. The largest frequency range, 10 kHz–18 GHz, is covered by the absorber lined chamber method [**10**]. However, the frequency range of interest for coupling of an electromagnetic field to a wire harness is up to a few hundred MHz [**15**]. Above this frequency coupling is directly to the internal circuitry of components, such as an electronic control unit, attached to the wire harness. This is because internal circuitry conductor lengths on the order of mm resonate at these frequencies. Initially, therefore, the tri-plate line method [**21**] was chosen for the tests, because it allows the frequency range of interest of around 10 kHz–500 MHz to be covered. In this test the component under test and associated wire harness is exposed to an electric field. However, no signal was detected in the samples in preliminary tests using this fixture, probably because of insufficient field strength achievable using the available equipment. The test finally selected was therefore not a standard automotive test but one intended to test cable shielding, similar to reference [**22**]. The principle of the test is to pass an RF current through a fixed, unshielded cable and to measure the amount of power coupled into the cable under test. The fixture is described in more detail below.

3 EXPERIMENTAL DETAILS

3.1 Cable tester

The cable tester, illustrated in Fig. 4, consists of an unscreened, insulated noise-generator wire stretched between two RF connectors on a supporting board. A test sample is taped to the noise-generating wire and the maximum RF current induced in the sample measured at a given excitation frequency. The generator wire is terminated to earth through 50 Ω. The test sample is connected to a twisted wire pair signal cable inside a screened box. The length of the sample protruding from the screened box and strapped to the generator wire is fixed at 485 mm. The test set-up was situated inside a screened chamber with the RF generator and EMI test receiver outside.

The signal in the test samples was below the detectable limit for the test receiver for frequency less than 1 MHz, so frequency scans were carried out between 1 Mhz and 30 Mhz with a 1 Mhz step and a nominal field strength setting of 10 V/m, and between 30 MHz and 1 Ghz with a 50 MHz step and a nominal field strength setting of 3 V/m. Note that the actual value of field strength is not important because these are comparative measurements.

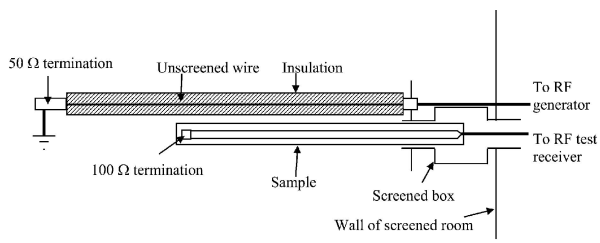

Fig. 4 Cable tester

The two lines of the sample circuit are connected together at the end inside the chamber with a 100 Ω non-inductive resistor. The signal cable is taken through a lead-through pipe outside the screened chamber and the two lines connected together with another 100 Ω non-inductive resistor. The current in the signal cable is coupled to the test-receiver using a ferrite ring. The coupling is arranged to measure differential mode noise, according to reference [**23**], Annex I. The coupling method was chosen so that the conditions of the sample circuit are as close as possible to those of a real CAN bus, i.e. neither bus line is earthed and the circuit is terminated at either end in 100 Ω. Samples were taped as closely as possible to the generator wire. Variation of the signal in the samples when they were removed and then re-attached was less than 3 dB.

3.2 Samples

Two cable samples were used consisting of a high-quality, twisted wire pair manufactured for use in an automotive wire harness and a single wire with a ground return. These were compared with five different FPC samples consisting of a pair of coplanar, straight tracks; two coplanar samples with different widths of aluminium shielding; a PTH 'twisted pair', as in Fig. 3; and a similar, zigzag track pattern without through holes, illustrated in Fig. 5. All the samples were 690 mm long, this being the maximum length that could be produced by the FPC production equipment.

The automotive twisted wire pair had 74 360° twists/m and a characteristic impedance of 82 Ω. The single wire was taken to ground through a 100 Ω non-inductive resistor at both ends. The FPC circuits were etched from a laminate of 75 μm PE and 35 μm copper. The unshielded coplanar track FPC sample had an impedance of 130 Ω. The shielded samples consisted of coplanar track FPC samples with shielding applied. A 50 μm-thick aluminium tape with an adhesive backing forms the shielding, applied in a sandwich structure with tape on both the top and bottom surfaces of the FPC and a layer of PVC insulation tape on top of the coplanar tracks. The top and bottom shields are entirely separated from each other along the length of the circuit by the base laminate of the FPC; i.e. 360° shielding is not achieved. The aluminium tape width for one sample was 10 mm and for the other 25 mm. The pattern repeat frequency for the PTH FPC was ten repeats/m and for the zigzag FPC 139 repeats/m.

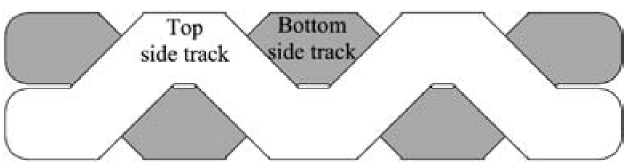

Fig. 5 Track pattern of sample used in EMC comparison tests

4 RESULTS

Figs 6(a) and (b) show the spectra measured with the twisted wire pair, the loose wire and the coplanar track FPC samples over the low- and high-frequency ranges respectively. A systematic difference between samples can only be seen in the low-frequency range up to around 20 MHz, with resonance effects dominating above this frequency. The coupling to the twisted wire pair is around 20 dB smaller than to the loose wire over this low-frequency range and is smaller than the noise floor of the measurement set-up of 5 dBμV/cm at 1 MHz. In the following discussion the loose wire and wire twisted pair spectra are used as benchmarks for the best and worst performance of wires in a wire harness and compared with the performance of the FPC structures over the frequency region below 20 MHz.

The difference in coupling between the coplanar tracks FPC and loose wire is relatively small, between 3 dB and 10 dB over the low-frequency range. This reduction in noise coupling, however, can be achieved at very little cost in the context of a large-area FPC harness and so would be a first-step ameliorative measure for EMC problems. The spectra for the PTH and zigzag track FPC samples can be compared from Fig. 6(c). The performance of the PTH pattern is identical to that of the twisted wire pair, within experimental error. The zigzag pattern gives a reduction in coupling over the loose wire of between 6 dB and 25 dB over the low-frequency range. This performance is midway between that of the coplanar tracks and the PTH pattern, but is again achievable at a minimal cost in the context of a large-area FPC harness, because no through holes are required. Zigzag pattern tracks have the disadvantage compared to coplanar tracks of taking up a larger area of the circuit panel.

The largest reductions in coupling strength over the loose wire were seen with the shielded samples, as can be seen from Fig. 6(d). The performance is even better than that of the wire twisted pair for the 25 mm shield, which provides up to 40 dB reduction in coupling. Note this is masked in the measurement at the lowest frequencies by the 5 dBμV/cm noise floor of the measuring equipment. The 10 mm shield provides between 17 dB and 30 dB of coupling reduction. The wider shield provides better protection because of the greater attenuation of radiation penetrating through the aperture between the shielding layers. Requiring the application of shielding would increase the production cost of an FPC harness, but lamination of a shielding layer to the circuit is more compatible with reel-to-reel processing than through-hole plating. It should also be noted that use of shielding reduces the characteristic impedance of transmission lines. Narrower and thinner shielding would be preferable from the point of view of material cost and reduced space utilization on the FPC panel.

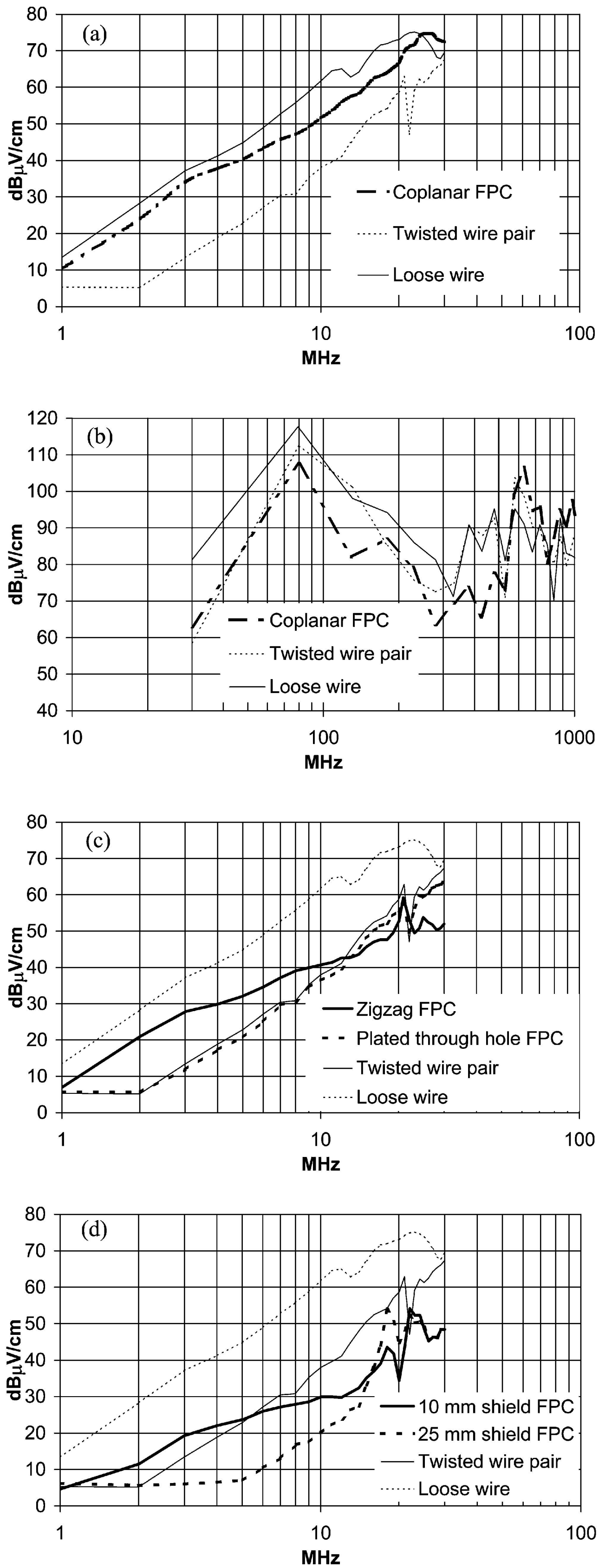

Fig. 6 Signal spectra measured in the cable tester

5 CONCLUSIONS

The implications for EMC of using a large-area FPC as a replacement for an automotive wiring harness have been examined. The need for measures available to FPC harness designers to ameliorate EMC problems in future FPC harnesses, similar to measures available to wire harness designers, has been identified. The effectiveness of the measures available to FPC harness designers, compared to the effectiveness of the measures available to wire harness designers, have been compared experimentally in a standard test. The results may be used to rank the FPC track structures by increasing cost and performance as follows:

1. Coplanar tracks (cheapest, lowest performance)
2. Zigzag pattern tracks
3. Shielded tracks (most expensive, best performance)

Additionally a through-hole plated track pattern was observed to give as good a performance as wire-twisted pair. However, this option is only possible if through-hole plating can be incorporated into reel-to-reel automotive FPC production lines. This is problematic because of the relatively long processing time required by the through-hole plating process.

The increased cost of manufacture of implementing options 1 and 2 are almost negligible. These options therefore represent the first resort for a designer wishing to improve the EMC performance of an automotive FPC harness.

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