Automotive Power-Line Communications : Favourable Topology for Future Automotive Electronic Trends

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Abstract

This paper argues the promising possibilities of power-line communications applied to automotive vehicles. In section 1 the importance of weight and cost in the automotive industry is discussed. Section 2 summarises the traditional automotive wiring method whilst section 3 discusses the growth of automotive electronics and associated challenges. Integration of components (section 4) and multiplexing (section 5) are discussed next, as these have reduced the complexity of wiring harnesses. In section 6 power-line communications is shown to facilitate a favourable topology for simplifying the wiring network. Section 7 discusses some possible current and future obstacles to power-line communications in motor vehicles, after which a short conclusion is made in section 8.

1. The automotive industry and some driving forces behind it

Competition between different manufacturers in the automotive industry is extremely fierce. When a potential buyer selects a new motor vehicle, be it for private or company purposes, some of the main deciding factors include: price, performance, fuel economy, safety, luxury, reliability and maintenance costs. These factors are often interdependent and are typically considered by comparing models from different manufacturers. Let us compare some features of three recent 1600cm^3 models available in South Africa [1]. See table 1.

It is clear that the three cars are very similarly priced - this fact reflects the stiff competition between manufacturers. Note that the cost difference between the highest and lowest priced vehicle is less than R2010[1] – an amount quickly saved by consuming less fuel or paying less for servicing costs. Expressed as a percentage, this difference in cost is only 1,7%. The value of a motor vehicle is not only determined by performance and fuel economy, but also by many other factors such as safety, luxury, reliability, maintenance costs, and even perceived second-hand re-sale value.

Table 1. Comparison of three recent 1600cm^3 motor vehicles [1].

Manufacturer, Model	**Renault Clio1,6 Dynamique**	**Nissan Almera 160 Luxury**	**Citroën Xsara 1,6**
Price	R118 990[1]	R121 000[1]	R118 995[1]
Performance	4 cyl, 1598cm^3	4 cyl, 1597cm^3	4 cyl, 1587cm^3
	79kW @ 5750rpm	81kW @ 6000rpm	80kW @ 5750rpm
	148Nm @ 3750rpm	138Nm @ 4000rpm	147Nm @ 4000rpm
	0-100 km/h in 9,94s	**0-100 km/h in 10,81s**	**0-100 km/h in 11,5s**
Fuel economy	8,25 l/100km	9,24 l/100km	8,61 l/100km

Interestingly, the three engines have almost identical specifications. One would also expect the acceleration of the three vehicles to be very similar (printed in bold, table 1). Surprisingly, the Renault outperforms the Nissan by almost a second and the Citroën by more than a second, when accelerating from 0 to 100km/h. Apart from the influence of the gearbox and other minor factors, the answer to this startling observation is the weight of the cars: the Renault weighs in at 1068kg compared to 1157kg and 1176kg for the Nissan and Citroën respectively [1].

Note that the lightest car has the best acceleration figure whilst the heaviest car has the worst. The lightweight Renault also uses less fuel than the others for obvious reasons. By building a vehicle that is not only cheaper, but approximately 100kg lighter than the others, Renault puts tremendous competitive pressure on other manufacturers.

Thus the general philosophy for automotive manufacturers is to optimise performance, fuel economy, safety, luxury,

[1]Currently one United States Dollar ($1) ≈ ten South African Rand (R10).

reliability and maintenance at the lowest possible cost and lightest possible weight. Power-line communications can have a major impact on cost and weight, as is discussed in the following sections.

2. Traditional wiring harness system

The traditional way of wiring a motor vehicle, is to use an insulated copper cable to deliver power (12V dc) to each and every component that needs to be switched via a mechanical control switch or relay. Furthermore, all sensors would send information back to the appropriate control unit through its own, dedicated cable. In some cases the earth (return) wire is shared, and in some cases the metal vehicle body is used as an earth connection. All these loose wires are then bundled together as effectively as possible to minimise installation/assembly time and cost. Fig. 1 shows some wiring harnesses. A few of these harnesses would make up the total wiring harness system.

Fig.1. Examples of wiring harnesses [www.delphiauto.com].

Note that these harnesses are very labour intensive to manufacture and install. Each wire needs to be cut to the correct length before assembly. Harnesses are delivered complete with crimped terminal connections. During vehicle assembly, the harnesses have to be routed through, and fixed to the vehicle's different compartments, and finally every connector has to be inserted into the correct terminal. The wiring system of some late models consists of up to 23 harnesses incorporating over 700m of wire [2]. Testing and faultfinding is very difficult and time consuming because of the maze of unidentifiable wires.

3. Automotive electronics growing exponentially

In the past 50 years, the average wiring harness weight of a motor vehicle has increased from 4kg to 91kg [3]. This 2300% increase in weight is a direct result of an increase in complexity of the wiring harness caused by an increase in the overall electronics content of motor vehicles. Thus the weight of a motor vehicle wiring harness is of the same order as the total weight difference between the motor vehicles discussed in section 1 (approximately 100kg). This implies that a reduction in the weight of the electrical wiring harness can have a significant impact on the overall weight of the vehicle.

The steering wheel of a new motor car may contain an airbag, hooter switch, indicator and headlight switches, wiper controls, cruise controls and even radio or cellular phone controls [4]. A modern motor vehicle driver door may contain mirror controls, window controls, door lock controls, speakers and courtesy lights. The wiring harness, feeding power and signals to these, have become so thick that it has, for instance, become a major difficulty to route to the steering wheel and driver door [4]. The wiring harness to a door can be as thick as one's wrist, consisting of up to 60 wires and is therefore not very flexible [5]. This makes manufacturing and assembly time consuming and costly, but also puts strain on the copper cable and thus degrades reliability.

Some future trends in automotive electronics seem far-fetched, but these have already been implemented by research laboratories [6-8]:

- Mobile digital internet and multi-media access to keep passengers busy.
- Vivid head-up displays on the windscreen, including car instrumentation, road maps, radio screen, etc.
- Automatic radar collision avoidance integrated with the cruise control system.
- Automated highway control of all vehicles by one supervisory system to increase throughput and avoid accidents.
- GPS navigation system, possibly with speech synthesis, guiding a driver through an unknown suburb.
- *X-By-Wire* where *wire* refers to the electrical control of actuators instead of traditional mechanical / hydraulic control, for instance electrical throttle control, steering-, braking-, clutch- and even suspension control.

Some advanced safety sensors include [6-8]:

- Traction sensor for ABS / traction control.
- Yawn sensor to help detect driver fatigue.
- Tyre pressure sensor to warn driver.
- Accelerometers to pre-detect accident conditions and implement active suspension adjustments.
- Sensors to control combustion and emissions.

It is clear that the relative cost of electronics in motor vehicles will only rise as manufacturers compete to provide optimum performance, fuel economy, safety, luxury, reliability and maintenance at the lowest possible cost and lightest possible weight. Furthermore, many mechanical and hydraulic functions are replaced by electrical systems, mostly under the so-called *X-By-Wire* umbrella.

It is predicted that between the year 2000 and 2010, the cost incurred by electrical / electronic functions would contribute 20 to 25% of the total manufacturing cost of a motor vehicle [9,10]. It is also estimated that the cost of the wiring harness contributes to 15% of this figure, implying that the wiring harness contributes 3% of the total cost of a motor vehicle. Compared to the 1,7% cost difference between the four motor vehicles discussed in section 1, it is clear that a cheaper wiring harness can have a substantial impact on the total cost of a vehicle.

4. Integration of components and modules as a counter measure

The complexity and cost of wiring harnesses is such a universal problem in the automotive manufacturing and design industry that the issue is addressed through various design strategies. The designers of electronic control units have integrated some of these units to do away with interconnecting cables, and have shifted the position of the unit/s to reduce wiring complexity. As a typical example, engine control, transmission control and throttle control (previously three separate units at three separate locations) are all integrated in one module called the powertrain control module (PCM) which is mounted directly on the engine [11]. See Fig. 2 (from [11]).

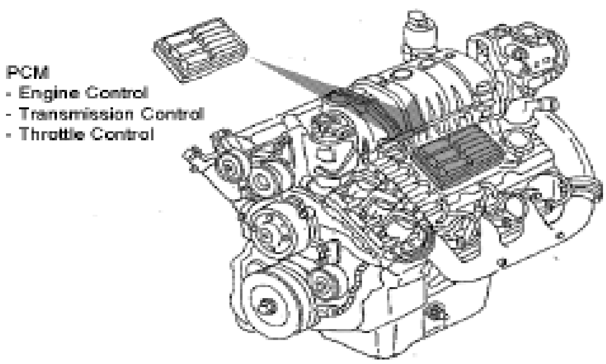


Fig. 2. Three modules integrated into one powertrain control module [11].

Engine control units typically have between 25 and 200 I/Os (in/outs or connections to other circuits) and communication is necessary with the other two modules. By integrating the three units, the wiring of some of these I/Os are now done inside the integrated unit, relieving the wiring harness of some of its duties. By shifting the position of this integrated PCM unit from the passenger or engine compartment to the engine (as close as possible to where the function needs to be fulfilled), wiring distances between the different sensors, actuators and modules are drastically reduced, making the wiring harness lighter, cheaper and simpler to manufacture and install.

Other designers now integrate electrical components into mechanical systems, to achieve exactly the same results by drastically shortening interconnecting wires. Typically, electronic control circuitry with its dedicated sensors and power electronic actuators are integrated or built into the mechanical system that needs to be controlled. Examples include integrated alternators and integrated electric power steering units [12].

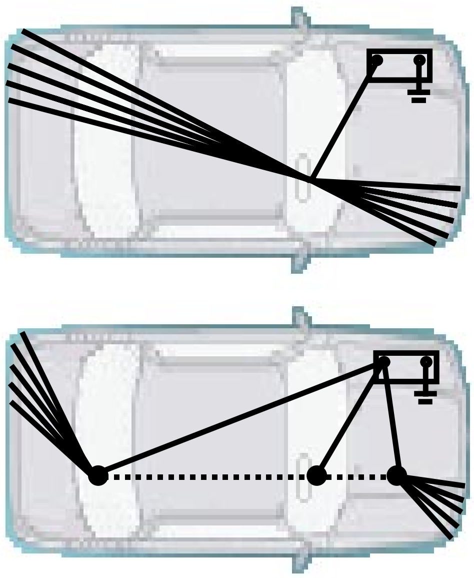
5. Multiplexed systems as a counter measure

The use of time-division multiplexing to reduce wiring harness complexity in motor vehicles, dates back to the late 1970's. Unfortunately the cost associated with the semiconductor ICs involved, made it impossible to be implemented economically before the 1990's [13]. In the mid 1990's three multiplex bus categories were defined by the Society of Automotive Engineers, called classes A, B and C [4]. The use of multiplexing has grown to such an extent that almost 40 protocols are currently in use, and that new categories need to be defined for specialized applications [14].

Let us consider the wiring layout of a multiplexed system compared to a traditional one. Fig. 3 limits the scope of application to two corners of the vehicle. The rear corner could include indicator, brake, park, reverse and number plate lamps, while the front corner involves indicator, head (bright / dim) and fog lamps as well as the hooter.

As can be seen in Fig. 3 b), the thickness and weight of the wiring harness is reduced drastically between the ignition and the multiplexed nodes. Unfortunately, every single node of the communication bus still needs to be supplied with power. Also, a complicated communication system is introduced. This increase in manufacturing and assembly cost, together with semiconductor expenses, typically cancels the cost savings obtained by the lighter power cabling system. To summarise, it can be said that multiplexing facilitates a lighter, more sophisticated electrical wiring system at the expense of increased complexity and cost.

Currently many researchers are working on optical fibre multiplexing network solutions [15-17]. The two main advantages of optical fibres are immunity against EMI and minimal weight. The main disadvantages are manufacturing costs, complexity and faultfinding / maintenance costs. Also, the electronics involved in converting the optical signal to an electrical one, is still vulnerable to EMI [15]. Nevertheless, the philosophy behind using fibre-optics is to totally separate control signals (electrically and magnetically) from power signals while travelling through cables.



a)

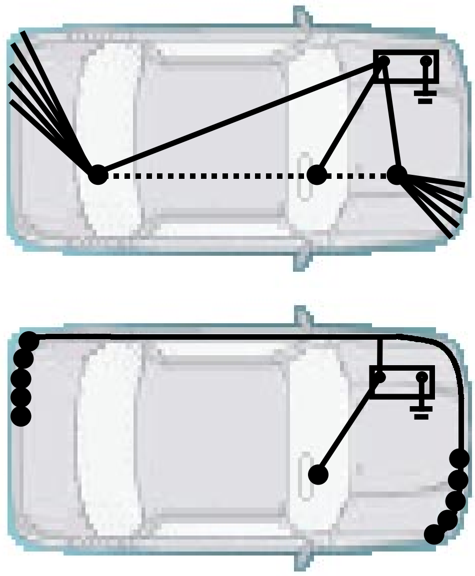
b)

Fig. 3. a) Traditional cabling system versus b) multiplexed cabling system. Solid lines indicate power cables while the dashed lines represent a communication bus. Black dots (nodes) represent the interface between power and communication circuitry – this is where multiplexing takes place.

6. Power-line communications as the ultimate solution

Power-line communications, in contrast to fibre-optics, ‘mixes’ control and power signals: a communication waveform is superimposed onto a power waveform, thus utilising the power line for both the distribution of power as well as information. Architecturally, power-line communications is the ultimate solution for automotive electronics. See Fig. 4.

The fundamental reason for this simplified architecture, is that no additional communication network or cabling is necessary. No simpler architecture exists, because power will always have to be delivered to every single load. Apart from the advantages of a very simple system that is easy to manufacture and install, faultfinding is simplified to such an extent that even a circuit diagram is unnecessary. Reason is that the communication and power signals share one physical network, which can be tested by checking for a 12V dc voltage on the shared bus. If the cable network functions, the load (e.g. light bulb) can be tested. If not faulty, either the sender or receiver node is faulty. Typically, the receiver nodes would be mass-produced, multi-purpose modules that can easily be replaced and then programmed by the motor vehicle’s main computer before resuming the trip. Thus the fault-finding process is reduced to an easy four-step process without requiring any knowledge of the circuit diagram.



a)

b)

Fig. 4. a) Multiplexed cabling system vs. b) power-line communications system. Black dots represent transmitter / receiver nodes.

7. Current and future challenges to power-line communications and possible solutions

7.1. New 42V dc *‘powernet’* standard

Automotive electronics is growing rapidly and becoming very sophisticated. The 2kW predicted power demand of these active circuits is such that the current 14V system (12V battery charged at 14V) would be inadequate for models planned for 2005 and later [18]. A quick solution would be to use a bigger alternator charging two batteries in parallel. But a low voltage such as 14V, forces one to use bigger currents in order to deliver more power. Current (current density) again determines cable thickness. Thus, if one keeps the voltage as it is, cable size has to increase to accommodate larger power transfer. At a specific maximum current, the new 42V standard could deliver 300% more power using the same cable. Conversely, the same power can be delivered using a cable with a 42% smaller diameter - the higher the supply voltage, the thinner and lighter the wiring harness.

The above-mentioned facts would have very little impact on power-line communications, but the details do:

manufacturers are suggesting a hybrid 14V / 42V system and are still debating whether one or two batteries will be used. Nevertheless, switching power electronic converters will be used to convert between the two voltage levels. These converters are operated at high frequencies to minimise their physical size and cost, and produce hostile high-frequency noise. Designers of power-line communications equipment would have to carefully consider the noise characteristics of different converter topologies.

7.2. Possibly an ac electrical system

Researchers are investigating the possibility of implementing an ac electrical system in motor vehicles – even three-phase systems are considered [19]. In the aerospace industry, a 400Hz ac system has already replaced dc to reduce the weight of cabling. Apart from weight considerations, transformers can step ac voltages up or down, producing less noise than switching dc-dc converters in dc systems. This doesn't eliminate power electronics from the system though, because a dc battery is used to store energy. The dc voltage needs to be inverted to ac, and is either done using an economical, noisy, square wave inverter or a more expensive resonant converter (which eliminates harmonics as waveforms are close to sinusoidal).

Single phase or three phase ac systems represents no obstacle to power-line communications, as the majority of power-line communication applications have been on ac lines. Once again, the waveform and noise produced by power electronic inverters have to be carefully considered in order to minimise detrimental effects on the communication signal.

7.3. Multiple communication networks necessary

In the near future as many as seven or more communication buses may be required to serve the different control and communication purposes of modern motor vehicles [14]. It is proposed that the SAE classes A, B, and C [4] are kept and that four extra dedicated buses are used for diagnostics, airbag, mobile media and X-by-Wire (thus seven buses in total).

At a first glance this poses a threat to power-line communications as only one power-line network currently exists. Fortunately, the network architecture of power-line communications is so simple and cost effective, that a seven-core power cable can easily be routed through the passenger and engine compartments, distributing power as well as seven separate communication signals.

In such an application, the simplicity and low cost of power-line communications are exploited even further: one multi-core power cable network replaces a complex web of seven multiplexed communication networks as well as the appropriate power cables. Refer to Fig. 5. The complexity of Fig. 5 a) would be seven-fold, while Fig. 5 b) stays the same, although the power cable would consist of seven insulated strands.

7.4. Government regulations

Although low-voltage (LV) power-line communications in Europe and South Africa is governed by the CENELEC standard EN 50065-1, other countries such as USA, have standards that are totally different to CENELEC's. As is well known, the EN 50065-1 standard imposes strict control over PLC equipment – public users are restricted to a 122 dBμV (≈1.25V) level between 95kHz and 148.5kHz [21]. On the contrary, USA companies are already producing commercially available low-voltage PLC systems operating in the 4.3 to 20.9MHz frequency range. These systems achieve 14Mbps data rates and comply with the USA FCC class 15 regulations [22].

European PLC experts are in agreement that higher frequency bands will have to be allocated to power-line communications in future. Dostert [21] suggests 3 possible bands between 1MHz and 10MHz for access use, as well as 7 possible bands between 10 and 30MHz for indoor use. If utilisation of these possible bands is granted, their potential would still be limited by government regulations on radiation levels (for electromagnetic compatibility reasons). These also differ radically from country to country. At 20MHz for instance, Britain allows an electric field strength of only 8 dBμV/m radiated from a wire-bound communication signal, whereas Germany and USA allow 30 and 70 dBμV/m respectively [21].

As for automotive applications, no standard has yet been defined. This gives the developer some freedom in terms of frequency utilisation and signal power levels. Motor vehicles will have a relatively small impact on one another as no conducted electromagnetic interference (EMI) is spread to other vehicles, only radiated EMI. The metal body of a motor vehicle further reduces radiated interference because it acts as an electromagnetic shield, similar to a Faraday cage.

The fact that the PLC system of any specific motor vehicle will have a relatively small impact on electronic systems in other cars, will definitely allow the utilisation of higher power levels at higher frequencies (provided that electronic systems within the motor vehicle itself is not adversely affected). If the USA FCC part 15 is used as a measuring rod, bit rates of up to 14Mbps is certainly possible [22].

8. Conclusion

Competition between automotive manufacturers is fierce, and motor vehicle weight and cost are two major competitive factors. Traditional wiring techniques causes the weight, complexity and cost of the power wiring harness to be directly proportional to the number of electrical / electronic devices used in the vehicle [20]. These devices have become so numerous, that the power wire required to service them, can in some cases not physically fit into the available space [13].

Power-line communications provides a network architecture in which only one (probably multi-core) power wire network is necessary, independent of the number of electrical / electronic devices used. However, it must be emphasised that the number of transmitter / receiver nodes is directly proportional to the number of devices, and would have to be cheap, mass-produced, integrated modules.

A power-line communications network architecture holds the potential to drastically reduce the weight and cost of the automotive wiring harness. It has been shown that the weight and cost of the wiring harness itself is of the same order as the weight difference and cost difference between competing motor vehicle models. Furthermore, faultfinding and maintenance of the power / communication network is simplified to such an extent that even a circuit diagram becomes obsolete. To automotive manufacturers, power-line communications could either mean the competitive edge over the opposition, or being dominated by the opposition – depending on who implements it timely, reliably and economically.

Acknowledgements

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References

[1] J. Wright (ed.), "Car Guide," *Car*, vol. 46(1), ISSN 0008-5995, pp. 193-203, February 2002.

[2] S. Minquan *et al*, "New concept of vehicle intelligent harness system design," *Proceedings of the IEEE International Vehicle Electronics Conference (IVEC '99)*, vol. 1, pp. 451-454, 1999.

[3] D. Sparks et al, "Multi-sensor modules with data bus communication capability," *SAE Technical Paper Series*, 1999-01-1277, Society of Automotive Engineers Inc, 1999.

[4] M. Thompson, "The thick and thin of car cabling," *IEEE Spectrum*, pp. 42-45, February 1996.

[5] W. Myers, "IC's per vehicle increasing rapidly," *IEEE Micro*, pp. 4-6, February 1993.

[6] W.B. Ribbens, *Understanding Automotive Electronics*, 4th Edition, Carmel: SAMS, 1992.

[7] J. Auzins, R.V. Wilhelm, "Automotive electronics – getting in gear for the 90's and beyond," *IEEE Circuits & Devices*, pp. 14-18, January 1994.

[8] D.K. Ward, H.L. Fields, "A vision of the future of automotive electronics," *SAE Technical Paper Series*, 2000-01-1358, Society of Automotive Engineers Inc, 2000.

[9] E. Zanoni, P. Pavan, "Improving the reliability and safety of automotive electronics," *IEEE Micro*, pp. 30-47, February 1993.

[10] C.P. Cho, R.H. Johnston, "Electric Motors in Vehicle Applications," *Proceedings of the IEEE International Vehicle Electronics Conference (IVEC '99)*, vol. 1, pp. 193-198, 1999.

[11] G.W. De Vos, D.E. Helton, "Migration of powertrain electronics to on-engine and on-transmission," *SAE Technical Paper Series*, 1999-01-0159, Society of Automotive Engineers Inc, 1999.

[12] B.A. Myers *et al*, "Embedded electronics in electro-mechanical systems for automotive applications," *SAE Technical Paper Series*, 2001-01-0691, Society of Automotive Engineers Inc, 2001.

[13] J.V. DeNuto *et al*, "LIN bus and its potential for use in distributed multiplex applications," *SAE Technical Paper Series*, 2001-01-0072, Society of Automotive Engineers Inc, 2001.

[14] C.A. Lupini, "Multiplex bus progression," *SAE Technical Paper Series*, 2001-01-0060, Society of Automotive Engineers Inc, 2001.

[15] Lopez-Lagunas *et al*, "Bidirectional single fiber low-cost optoelectronic interconnect for automotive applications," *IEEE Transactions on Vehicular Technology*, vol. 49(1), pp. 281-286, January 2000.

[16] Y. Wu, H. Ikeda, "Parallel transmission of vehicle mirror control signals by a single optical fiber," *IEEE Transactions on Vehicular Technology*, vol. 45(4), pp. 760-767, November 1996.

[17] M. Lynn *et al*, "An expandable passive optical star network architecture for automotive applications," *SAE Technical Paper Series*, 1999-01-0303, Society of Automotive Engineers Inc, 1999.

[18] J.G. Kassakian *et al*, "Automotive electronics power up," *IEEE Spectrum*, pp. 34-39, May 2000.

[19] M. A. Masrur *et al*, "Can an ac electrical system replace the present dc system in the automobile? An investigative feasibility study – part I: system architecture," *IEEE Transactions on Vehicular Technology*, vol. 47(3), pp. 1072-1080, August 1998.

[20] Z. Rongliang, C. Xiaodong, "Electronic automotive wiring harness," *Proceedings of the IEEE International Vehicle Electronics Conference (IVEC '99)*, vol. 1, pp. 443-446, 1999.

[21] K. Dostert, *Powerline Communications*, ISBN 0-13-029342-3, Upper Saddle River: Prentice Hall PTR, 2001.

[22] http://www.intellon.com/products/powerpacket/