Analysis and Comparison of Scalextric, SCX, and Carrera Digital Slot Car Systems: A Mechatronic Engineering Design Case Study

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Abstract: Digital slot cars operate by transmitting both power and data over a single pair of wires much like DCC-controlled model railways and some home automation systems. In this manuscript we analyse and compare the cars, track, controllers, and electronic data transmission protocols of the three popular digital slot car systems.

Contents

1 Introduction

Over more than a century, slot cars have evolved from clockwork power to today's electrically-powered, remote-controlled, digital racers (Wikipedia 2014, Robertson et al. 1988). Along the way the technology has continuously improved much as it has with real cars (David 2014). Power advanced from clockwork to internal combustion to electrical. In the 1980s magnets improved adhesion much as ground effect changed formula car performance. More recently, as of about 2004, cars have appeared with digital control, where both power and control signals are passed through the track. Instances of heuristic and atrificially-intelligent autonomous slot cars have been reported (Brejl &

Necesany 2008, Kane & Scott 2008). Digital control, initially modelled on the DCC system used by model railway manufacturers (NMRA 2004), lead to robust systems allowing cars to change lanes, and to number greater than the number of lanes available in the track. Unfortunarely there is no standard system for slot cars as there is for model trains, and at least three separate and incompatible digital control systems have appreaed on the market. This manuscript compares the design philosophy and performance of these competing systems.

We purchased starter sets from the three companies and subjected each to rigorous analysis and use. The Carrera set was a "Digital 132 Formula 1 Champions" set number 30157. The SCX set was a "Basic Set" D10010. The Scalextric set was a "Digital Pro GT" set with some additional track. The sets are depicted in figure 1.

Figure 1: Promotional images of the three sets used in this teardown report.

The modern digital slot car system differs from its analog predecessor in essentially three ways. The track carries full voltage all the time, and combines a method to transmit digital instructions, much like a computer network, allowing more than one car to be independently controlled on the same circuit. Next, each car contains a low-cost microcontroller (small computer) whose job is to decode the instructions and drive the motor according to the digital instructions, derived from the drivers' hand controllers. Finally the track is augmented with "points" or "switches" that allow cars to change lanes.

2 The Cars

There are several physical differences between cars of the three digital slot car systems. These influence the overall cost of the manufacturing and the performance. We examined both "formula" (F1) body shape and "street car" body shape cars in the Scalextric and Carrera systems, but only the street type in SCX (the F1 models in the SCX range seem to use the same motor as the street models).

It can be seen (figure 2) that the Carrera cars were made using brass bearings, while the gears were all made out of plastic. In the Scalextric cars it can be seen that both the bearings and gears were manufactured using only plastic, which would reduce the manufacturing cost of these parts. In contrast to both of these systems, the SCX bearings and their pinion gears were manufactured using brass which is the most costly material. Even though the materials used within the SCX slot car may be the most expensive, they will be the most reliable and therefore it seems to be the highest-quality option.

All three cars use a different microprocessor in order to control the different aspects of the slot car. The Carrera systems contain Atmel microprocessors; the ATMEGA8A (NZ$2.50 RRP) is used within the car itself. This chip is an 8-bit microprocessor which runs at 16 MHz and does not use a crystal to increase the operating frequency or set timing. The Scalextric systems use Pic microprocessors, with the PIC16F630 (NZ$1.74 RRP) used within the car. This microprocessor is also 8-bit and can

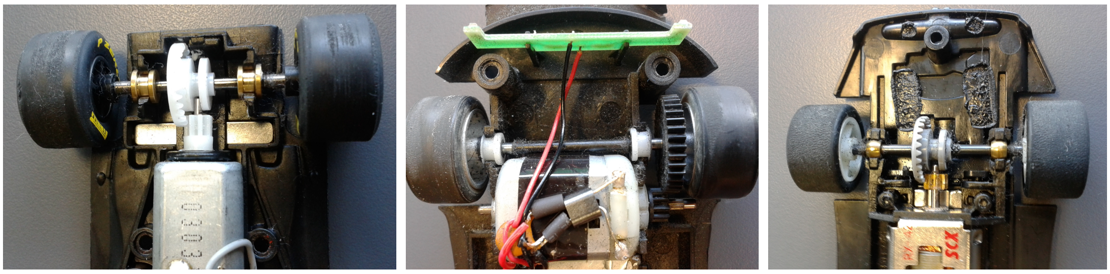

Figure 2: The bearings and gears of the rear axle of Carrera, Scalextric and SXC respectively.

run up to 4 MIPS. The Scalextric cars use a crystal in order to increase the operating frequency or set its rate precisely, but its frequency could not be determined owing to component placement. The SCX systems use freescale microprocessors, with the MC908JL3E CFAE (NZ$2.95 RRP) used within the car. This is an 8-bit microprocessor that utilises a 16 MHz crystal placed on the circuit board to set the operating frequency. A comparison of the three microprocessor families is beyond the scope of this report, and the reader is referred to Slade, Jones, & Scott (2011). This reference asserts that the Atmel series offer the highest performance.

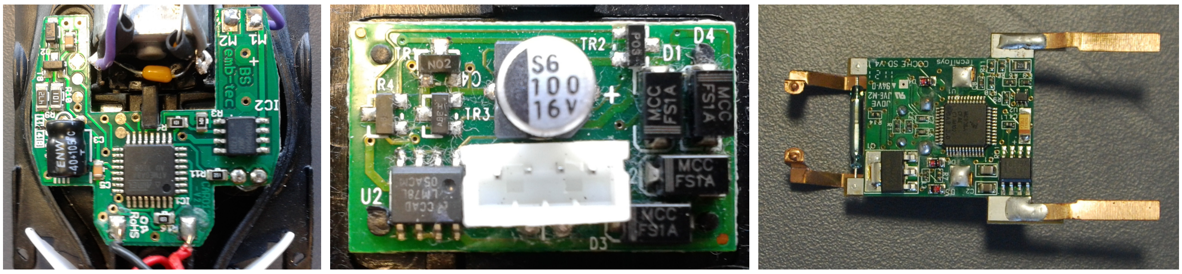

Figure 3: Electronic control circuit boards of Carrera, Scalextric and SXC cars respectively.

The methods of assembly differ for the three slot car systems. The Carrera system contains wires which are soldered to the circuit board as well as the motor and track connections. This makes assembly more difficult, and can make it difficult to replace parts or fix the circuit board when needed as unsoldering is required.[1] The Scalextric cars have wires that are soldered to the track connections, lights, and the motor, but they are all joined to the electronic circuit board (PCB) via a connector.[2] Using the connector means that the board can be easily removed for maintenance purposes. In contrast to both of these systems, the SCX cars do not contain any wires. They form electrical connections using springy copper fingers which, once produced, make the assembly of the car very quick and easy. The SCX car contains the best type of electrical connections due to the ease of manufacturing and repair. A disassembled SCX-brand car appears in figure 4.

[1]Our experience has been that it is the circuit boards that are most likely component to fail. One car failed twice and had its microcontroller and eventually the whole car replaced under warranty. A car in a different system was damaged through mishandling on our part while taking the car apart and putting it together again. In contrast to failure by "misadventure", there is no physical reason to expect the electronics to "wear out", whereas the mechanical parts might be expected to wear out as they do in a real car. The only fixed part that is anticipated to fail—apart from tyres and pickup braids that are recognised as "consumables"—in a shorter time than other parts is the motor, where the brushes will typically wear down and cause failure within a few tens or hundreds of hours' use. Motors are offered as a spare part by manufacturers.

[2]This practice has presumably been adopted from the world of model railways, where it is common to convert between analog and digital systems by the replacement of a bypass plug with an electronic printed circuit board (PCB).

Figure 4: An SXC car disassembled showing the spring contacts that replace soldered wiring and PCB connector plugs.

2.1 Motors

All three systems use permanent-magnet, brushed, dc motors. Carrera and Scalextric use "sealed can" type motors. SCX use a vented motor. The F1 cars used smaller motors rated for 17500 rpm. This motor drew more dc power when compared to the 18000 rpm-rated motor in the street bodies.[3] The 17500 rpm motors are a good choice for the F1 cars as they are thinner and fit in the skinny bodywork.

We carried out some characterisation of the three types of motors taken from street-style (not F1) cars in accordance with the theory for shunt dc motors (El Hawari 2002). From measured values of armature current with a locked rotor and the free-run velocity of the motors on a 12 V supply we calculated the theoretical maximum power, maximum (starting) torque, and maximum (no friction) velocity of three sample cars. We also measured the maximum speed. These results are summarised in table 1.

Parameter	Carrera	Scalextric	SCX
I_A (Locked rotor)	1.7 A	1.5 A	1.7 A
R_A	7Ω	8Ω	7Ω
V_{max} (free run)	5.8 m/s	6.8 m/s	5.2 m/s
K_e	15,000 RPM	22,000 RPM	13,000 RPM
P_{max}	7 Watts	6 Watts	7.2 Watts
Torque$_{max}$	13 Nmm	7.5 Nmm	14 Nmm
G (gear ratio)	27/10	38/11	27/10
V$_{max}$ (measured)	3.9 m/s	4.6 m/s	3.6 m/s

Table 1: Summary of performance to be expected from the motors in the three types of car. The motor electrical constant is calculated from estimated linear velocity V_{max} computed from tachometer measurement of the car running assembled but free of the track, using the formula $K_e = \frac{60GV_{max}}{\pi d_{wheel}}$ (value in RPM), where wheel diameter $d_{wheel} = 20$mm and G is the gear ratio. Note that there is some variation in wheel diameter on different prototypes.

The SCX motor provides the largest maximum power and torque under load when compared to

[3]These speed ratings are provided by the manufacturers. The standard Scalextric car spare motor, product code C8146, is described as rated for 18,000 rpm, while 25,000 rpm motors are available to "tune" the cars. See `http://www.scalextric.com/`. An RPM rating, measured under no load, is a method of specifying the crucial electromotive constant of a motor, the constant relating back EMF to shaft rotation speed, K_e (El Hawari 2002).

the other two motors as shown in the table—it has the most powerful motor. Nevertheless, when comparing the theoretical maximum velocities of the three cars it can be seen that the SCX actually produced the lowest value with Scalextric producing the highest. The maximum velocity was measured without load (not moving on the track) avoiding the on-track losses in pickup braids and tyres, but do include losses in gears, bearings, etc. For this reason we measured the velocity of the cars on a sample straight length of track as well. To measure the maximum speed, the cars from the three different systems were placed head-to-head in a 3 meter "drag race". The gear ratio of the motor to the cog determines the amount of power delivered to the wheels and therefore the speed and acceleration of the car. The gear ratio of the Scalextric car with sidewinder-type motor was 3.45 compared to 2.7. This larger gear ratio proved to be advantageous. The SCX car did not perform as expected. We attribute this to higher losses and less-suitable gear ratio. Overall, the Scalextric motor and design emerges as the best.

The Scalextric street-body cars used east-west (so-called sidewinder) motor orientation. This arrangement is common within 1:32 and 1:24 high performance slot cars. The advantages for these arrangements are that the reverse torque generated when the motor accelerates moves the centre of mass towards the front of the car. This then allows the slot cars to accelerate while they are racing around corners. As well as this, it has been shown that when the dynamic brakes are used, the centre of mass moves towards the rear wheels which gives more grip to tyres and therefore the track. Most of the slot cars examined used the inline motor arrangement, used because it takes up less space when compared to the other arrangements. The main disadvantage for this arrangement is that the reverse torque caused by the rotation of the motor also moves the centre of mass from side to side which can cause the slot car to become unstable. Nevertheless, in this case of domestic racing sets, the arrangement of the motors did not seem to have any dramatic effect on the cars.

2.2 Braking

The Carrera system can be programmed to have one of ten brake settings with level one being the softest (lowest level of) braking and level ten being the hardest (highest level of) braking. The increase in brake level from the lowest to the highest setting is significant and results in decrease of stopping distance by a factor of two or greater. The brake setting is activated when the trigger on the hand controller is released. The Scalextric system had only one brake setting associated with a button on the hand controller. The stopping distance of the car was found to decrease by a factor of approximately 2 when pressing the brake button compared to just letting go of the acceleration trigger. The SCX system had no additional braking features and relied solely on the release of the trigger in order to reduce the speed of the travelling car.

2.3 Magnets

The Carrera and Scalextric cars contain two magnets each, designed to improve adhesion to the track. The first is located across the centre of the car and the second is found just in front of the rear axle. The SCX car had one magnet located just in front of the rear axle. Refer to figure 5. These magnets significantly increased the traction of the car, so the car was able to travel at a higher speed before losing control and coming off the track.

In the case of the cars with two magnets, with both magnets installed in the car we observed that there was virtually no time to make any correction in speed between seeing the car sliding off course and the car shooting off the track. In effect, the driver was deprived of feedback that could allow "pushing the envelope" without flying off. We found that removing the magnet located just in front of the rear axle, allowing the rears of the cars to drift a little as they raced around corners progressively faster, opened the possibility of the driver dynamically adjusting speed without a certain risk of falling off. On one hand this is appealing, as the driver can demonstrate skill to accurately control the speed without the car falling off the track as is the case with real cars. On the other hand, the maximum speed is lower as the traction is lower. When racing in these conditions, it is essential to have the side barriers attached on all corners in order to provide extra protection for the cars and to help keep the car on the track when it starts to lose control. Track fences and edges became more important.

Removing both of the magnets from the two-magnet cars or the one magnet from the SCX cars causes the traction to be so low that the drag of the pickup braids becomes dominant and the cars are not workable, most of the time. Removing the magnet from the centre of the car causes the car to perform very similarly to when it has both magnets within the car.

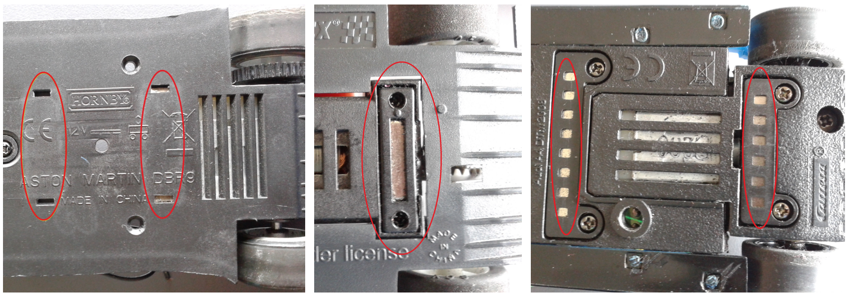

Figure 5: Picture of the positions of magnets in the three families, Scalextric, SCX and Carrera.

2.4 Car Lights

All three systems equip their street-body cars with head and tail lights illuminated by LEDs. The Scalextric LEDs, both tail and head, get brighter as the speed of the car increases (they are only on when the car is moving, as they are connected in parallel with the motor, as in a conventional, analog system). The SCX lights are controlled by an on/off button located on the main, trackside controller box. The Carrera LEDs turn on whenever the car is on the track. Figure 6 shows the electromechanical layout in the three cases.

The LEDs in Carrera and SCX are under the control of the microcontroller inside the car by means of a transistor switch on the PCB. The headlights in the Carrera system flash to signal that the car is in programming mode.[4] The taillights get brighter when the car slows down.

The headlights within the Carrera cars are used as part of the programming, in comparison with the other cars. The additional cost for the Carrera light system over the Scalextric would be small—and no more at all than that in the SCX cars—and therefore the Carrera system seems to be making the best use of its lights.

2.5 Car Identification and Lane-change

As noted in section 3, each car is individually controlled irrespective of which lane upon which it is racing. How does a lane change happen? Each manufacturer deals with car lane changes differently.

The Carrera and Scalextric systems use an Infra-red LED in the car to signal down to the track, much like a TV remote control. In the Scalextric, the LED is mounted in line with the slot, behind the fin

[4] Since there are no headlights on F1-style cars, their use by Carrera as confirmation of programming actions can make it very difficult to learn to operate the set. You will likely need a street-body car upon which to practice, as programming requires a few steps with careful timing. Refer to section 6.

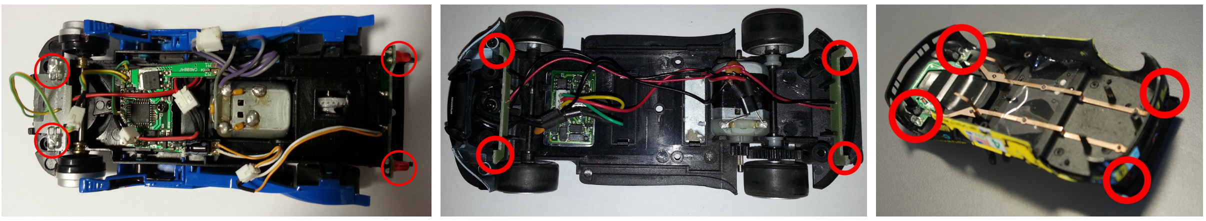

Figure 6: Details of the position and connection of the headlights and taillights within the Carrera, Scalextric and SCX slot cars.

that runs in the slot and separates the pick-up braids. In the Carrera system the LED is offset to one side of the car. The tracks have corresponding photoreceivers, see section 4.

In the Carrera system, the car signals its identity using the LED. The same data stream that is decoded in the car is also decoded by a similar microcontroller in the track. When the data stream is telling a given car (say #3) to change lanes, the track also knows this, and if a car wanting to switch approaches a switch point, the point recognises the car from its LED signature, and activates a mechanical diverter as described in section 4. Different cars are identified by the frequency of the flashing of this LED. Each controller sets the LED (on the bottom of the car) to oscillate at a slightly different frequency. This difference in frequency enables the car to be recognised. The frequencies set by the first 4 controllers are 15.63 kHz, 7.81 kHz, 5.21 kHz, and 3.91 kHz respectively, and it is not dependent on the type of car, only its address.

In the Scalextric system, the photoreceiver on the track also determines which car is passing overhead using a pulse-width/frequency. However, this system signals that the car wants to change lanes by inverting the polarity of the signal produced on the LED. This simplifies the job carried out in the track (we presume). The frequencies set by the 4 controllers within this system are 5.5 kHz, 4.36 kHz, 3.66 kHz and 3.02 kHz respectively.

The SCX system is set up differently when compared to the previous two systems. The slot cars do not contain LEDs but instead a solenoid. A mechanical lever is pulled down by the solenoid. The lever pushes a pin down into the slot in the track and this in turn switches a vane to let the car change lanes—see section 4 for more detail of the mechanical mechanism, and section 3 for a discussion of how the lane change is signalled. The pin runs through a hole in the guide fin itself, and when pushed it protrudes about 3mm lower into the slot. This system has the strong advantage that there need be no electronics in the track points. The impact is mostly on cost—SCX double crossover sections cost about NZ$20, while the points in the other systems cost about 4 times as much each. This would have a big impact on a large layout.

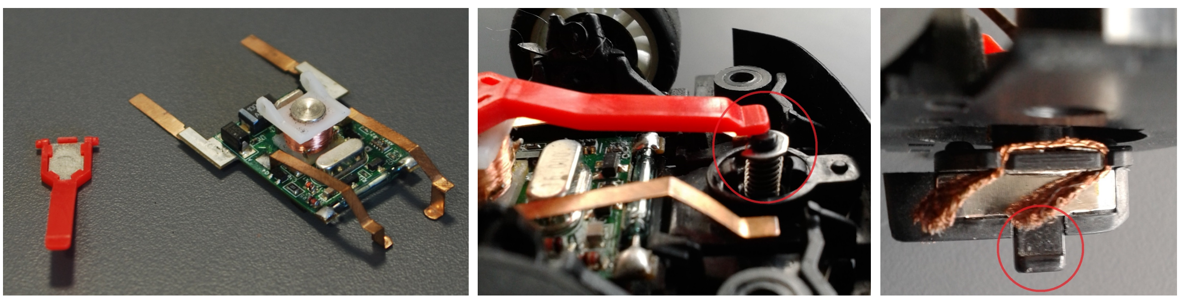

Figure 7: Picture of the lever and solenoid of the lane-change mechanism used within the SCX slot cars, and the finger that protrudes to cause a lane change. The lever hinges when clipped to the solenoid, and when pulled down by the magnetic field it pushes the sprung pin that extends deeper into the slot.

Comparing the three systems, the Scalextric one has the advantage that the track does not need to "be intelligent", but is otherwise similar to Carrera. The SCX system could offer enormous advantage as the track needs to contain no electronics at all. All three systems worked well in all our tests.

3 Communications Protocols

The three systems implement different kinds of power-and-data transmission over a single pair of wires. In each of the systems command data to control car speed and other car-based functions is passed through the track. Scalextric drives AC onto the track, coding the data using a version of frequency-shift keying modulation taken from the NMRA standard for DCC with an adapted packet protocol (NMRA 2004). SCX and Carrera drive DC onto the track, and encode data with momentary interruptions to the dc supply. Carrera codes the data with pulse-position modulation. SCX use simple Amplitude Modulation (AM) following a synchronisation byte.

The Scalextric and Carrera cars are equipped with IR LEDs that point down towards the track. These are used to "uplink" data from the car. The Carrera cars uplink their identity. The Scalextric cars uplink both their ID and their desire to change lanes. The SCX cars do not appear to uplink any data, although we did not search for data in the track current.

We have observed that when an SCX car crosses the starting grid the thrust and lights of all the cars are briefly interrupted. The starting-grid track contains reed switches that seem to be intended to detect passing cars via their traction magnets. The circuit boards in the cars we examined also carry reed-relay switches that respond to magnets situated in the track. This may be some sort of lap counting mechanism, although it is not obvious how it might work. The power interruptions can be annoying, much like those encountered crossing switchover tracks.

You may skip the remainder of this section if you are not interested in the details of the digital data transmission.

3.1 Scalextric

Scalextric uses a system based on the DCC standard (9.1 and 9.2) published by the NMRA (NMRA 2004). In this system a squarewave is driven onto the track, with the period of the wave encoding 1s and 0s. A positive half cycle of about 56μs followed by a negative half cycle of the same duration encodes a logical 1, while a half-period of double that encodes a logical 0. A packet is started with a preamble consisting of at least 13 1s in a row. Bytes within the packet are separated by a zero bit. An example data packet in the Scalextric is shown in figure 8.

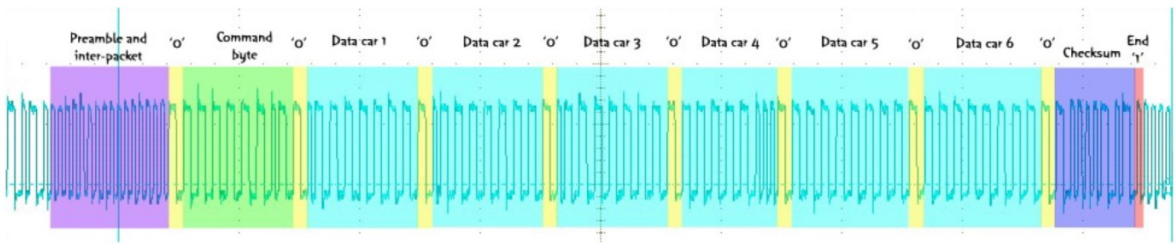

Figure 8: Scalextric data packet showing the breakup into bytes.

In normal operation, the command byte takes the value 0x02. The individual car bytes carry speed, lane change, and braking instructions. Programming is achieved through changing the command byte to 0x01, at which point the target address is sent in every car's byte position. All cars on the track move to the designated address.

The length of packets is not fixed, because it takes twice as long to send a 0 as a 1, and the preamble length is not limited. Nevertheless, an entire packet should rarely approach 8.5ms in duration, implying comfortably over 100 updates/second to each car.

7	6	5	4	3	2	1	0
BRAK	LANE	SPD-5	SPD-4	SPD-3	SPD-2	SPD-1	SPD-0

Table 2: Bit definitions of the Car Control byte for the Scalextric system.

Table 2 shows the definitions of the bits in each car's byte in the packet. Their meanings are:

BRAK Controller brake button pressed

LANE Controller lane-change button pressed

SPD-5:SPD-0 Speed of the car

The cars are equipped with an IR LED that points down to photoreceptors in the centre of the slot. The LED is used to signal the identity of the car, and the desire to change lanes. This mechanism allows a section of the track to identify any car passing above it, and also to simply work out if a lane change is to occur. For details see section 2.5.

3.2 Carrera

The Carrera protocol transmits data to the cars via the track through a sequence of 10 packets, evenly spaced 7.3ms apart, giving a total transmission time of 73ms, or almost 14 updates to each car per second. Each packet begins and ends with a pull-down, between which markers data is transmitted via pulse position modulation. Referring to the packet expanded in figure 1, the first part of the packet is a low (zero volts) about 50μs wide. The period of high levels is slightly longer, about 58μs. This packet is made up of 18 such periods. A "1" is conveyed by a high level followed by a low, and a logical "0" by a low followed by a high. This guarantees that the data packet will not have any long sequences of high or low levels. Observe that there are 8 pairs of half-bits between two end low-level periods in the example shown, so in this case 1 byte of data is being transmitted. Packets may vary in length.

The 10 packets are sent cyclically, and appear to have the following functions, though we have guessed the positions of car 5 and car 6 control packets as we have only a 4-car set: Mode byte, Lane-change (with even parity bit for 7 bit length), Car 1 control, [Car 5 control], Car 2 control, [Car 6 control], Car 3 control, Lane-change (repeated), Car 4 control, checksum (length 12 bits). The car control bytes have the format shown in table 3. Therein the bits are defined as follows:

ID-2:ID-1 The car numerical address (identity)

T Toggles lights when stopped, confirms various programming modes

SPD-3:SPD-0 Speed relative to the car's preprogrammed maximum

FT Enables or disables the Fuel Tank function

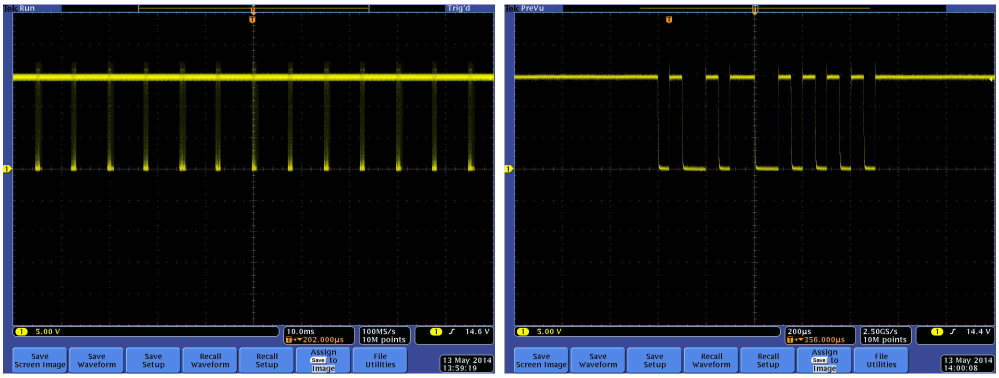

Figure 9: Carrera data transmission captured from the track using a storage oscilloscope. The image at left shows the bursts regularly imposed on the otherwise-constant dc level of abot 15V. Next to that one burst is seen expanded. This packet conveys the hex byte 0x90 or 0b10010000 binary.

8	7	6	5	4	3	2	1	0
ID-2	ID-1	ID-0	T	SPD-3	SPD-2	SPD-1	SPD-0	FT

6	5	4	3	2	1	0
CL-0	CL-1	CL-2	CL-3	CL-4	CL-5	Odd Parity bit

Table 3: Bit definitions of the Car Control packet and the Lane Change Control packet in the Carrera system. For the definitions, refer to the text.

Cars can be programmed by various toggling mechanisms from the controllers. It appeared from testing that the cars themselves monitor the state of each packet's toggle bit (T). When a car has registered two toggles from a controller (finger presses on the lane-change button while the car is not moving), and if it is removed from the track within a short time-out period, it enters programming mode (flashing its lights). Once returned to the track and power, two toggles indicates ownership programming, four toggles automatic driving, and six, pace car mode. These later toggles also have to happen within a short time-out period following the restoration of power, or the car exits programming mode and retains the original settings.

Speed and braking power are stored in the car, not the controller. For example, the controller can send a full-speed signal ('xF'), and the car will still only travel as fast as programmed to. We did not ascertain details of the mechanism by which the Carrera hub programs cars speed, fuel capacity or braking power, though it appears to use the Operation packet.

The car transmits its identification number using an IR LED mounted on the chassis, to one side of the slot, using a pulse-width modulation scheme. We speculate that lane changing is achieved by means of the microcontroller in the track. The track decodes the change packet that is visible on the rails, and upon detecting a car whose driver has requested a lane change, the track changes the point blade. In other words, the car does not know when it is changing lanes at all. It is likely that the ID transmitted by the car will allow lane counters to keep track of cars as they pass as well, though we do not have that accessory in the set we bought to confirm that this is how they work.

3.3 SCX

The controller sends a 9-packet serial sequence. A low voltage level is a logical "0", and full supply is logic "1". These bytes are sent in quick succession, whenever an input changes, or every 110ms or so if no change has occurred. It takes roughly 1.4ms for each sequence, at a bit speed of $\approx 115\text{k}$ baud.

Each byte consists of 10 bits, with 1 start bit, 8 data bits, and an even parity bit, sent little-endian, with LSB first. A capture of a burst of bytes is shown in figure 10 and the contents of a car control packet is shown in table 4. The meaning of the 9 bytes is respectively: start byte, Status byte, Car 1 control, Car 2 control, Car 3 control, Car 4 control, Car 5 control, Car 6 control, and finally a checksum byte. The car control packet bits are defined as

LGHT Car lights control

LCHG Tells the car to extend the lane-change finger.

SPD-3:SPD-0 Speed of the car

7	6	5	4	3	2	1	0
LGHT	LCHG	SPD-3	SPD-2	SPD-1	SPD-0	-	-

Table 4: Bit definitions of the Car Control packet for the SCX system.

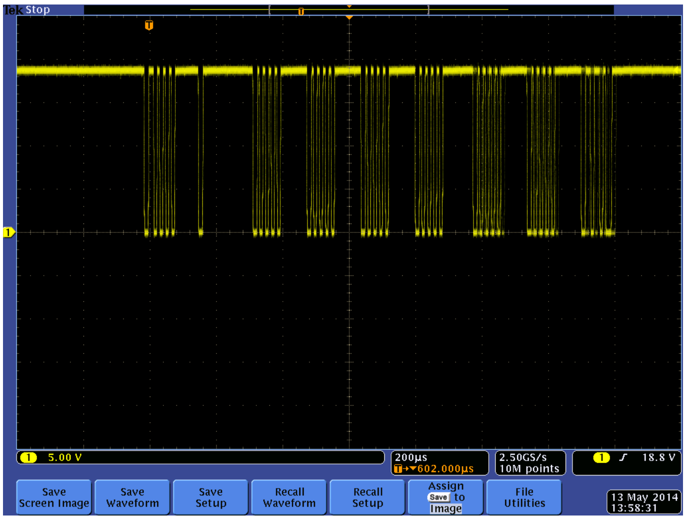

Figure 10: SCX data transmission captured from the track using a storage oscilloscope. The image shows the burst of 9 bytes.

The start packet consists of a series of alternating bits, 0xAB. The status packet has a value of 0xFF during normal operation. The car control packets, when their respective controller is not present, have a value of 0xAA. In programming mode, the respective controller packet is set to 0xFA. In normal operation, the car packet contains data regarding speed, lights, and lane change, as listed in table 4. Cars are programmed by placing the desired car on the track, pressing the program button, and then holding down the respective lane-change button. This changes the status packet to 0x32, and the applicable car packet changes to 0xF4.

4 The Track

The three systems share some design aspects but their lane change and lap counting mechanisms work quite differently.

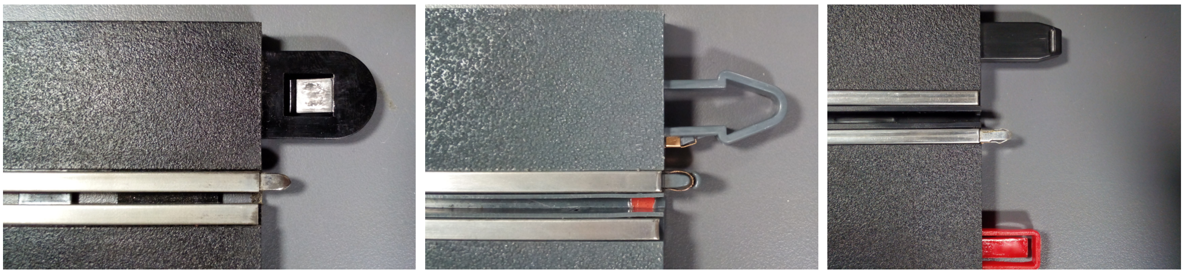

Figure 11: View of the connecting hardware for track in Scalextric, SCX, and Carrera sets respectively.

Figure 12: The track guards (perimeter and fence arrangements) for Scalextric, SCX, and Carrera sets, from top to bottom respectively.

4.1 Scalextric Track

The Scalextric tracks are made from soft black plastic material, they are flexible and bendable. Each track piece has a soft plastic clip at the end (refer to figure 11), which gives a relatively strong connection when attaching to the next piece. The undo process is also simple requiring a light press at the back of the clip so the tracks will disconnect. This is easy to achieve once you know to feel for the clip. The metal rail has a solid pointing connector at the end, which can be easily pushed into other rails. The width of the track is about 155mm, and the metal rails are about 4mm apart, the thinnest slot size of the three systems.

The lane-change track sections are of particular interest. The double lane-change track has X shaped rails. The switch where the car can follow one of two different paths is organised with a single "point blade", a section free to pivot, see figure 13. They are conductive but isolated from the rails at the pivot point. It can be observed that one of the rails swells a little at the very end of the lane changer, a small raised peak visible in the close-up. When the switch is set to the side (curved) direction, car momentum forces it to tend straight. The car's guide blade then hits the raised peak which prevents itself from directly smashing onto the end the lane changing point blade. The mechanism by which the blade is positioned will be discussed in section 4.4.

Use of the Scalextric system quickly exposes a problem with the switches. Cars that come to a stop while their brushes (pickup braids) are traversing the point blade become stuck. *This stalling quickly becomes annoying, and is a serious design issue*. Simple design changes to incorporate a capacitor in the car and alter the microcontroller code so that loss of supply instructs the car to continue rolling forward mostly cures the problem (McMullan 2012). Nevertheless, Scalextric have not incorporated this change. We speculate that the point blade is intended to connect electrically to one or other side of the slot, so that the point blade is powered, but this does not happen correctly. We measured a distance of about 105mm along which the car receives no power.

The Scalextric set offers an edge-guard accessory with fences for the corners. It is effective in preventing the cars from sliding off the track. Referring to figure 12, the top image shows a section designed to lead from straight track (with no guards) into the corners. The assembly consists of a flat portion a few cm wide that supports a moulded plastic fence. These barriers proved to be quite rugged and durable.

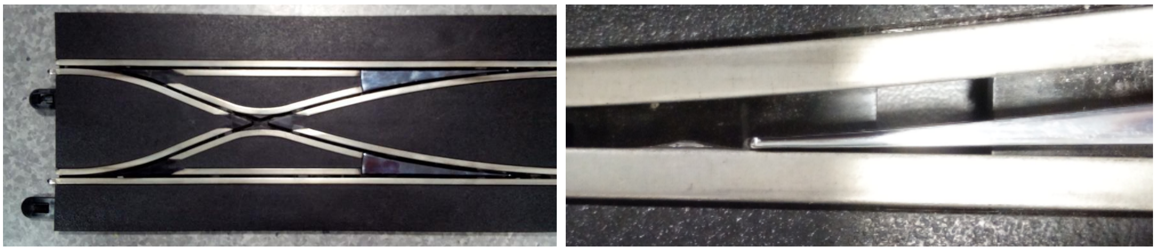

Figure 13: View of Scalextric double crossover section. The shiny silver triangular parts at the right are the point blades that guide the car. In the close-up the small bulge is visible in the lower side of the slot. This prevents the car's blade from hitting the end of the point blade.

4.2 Carrera Track

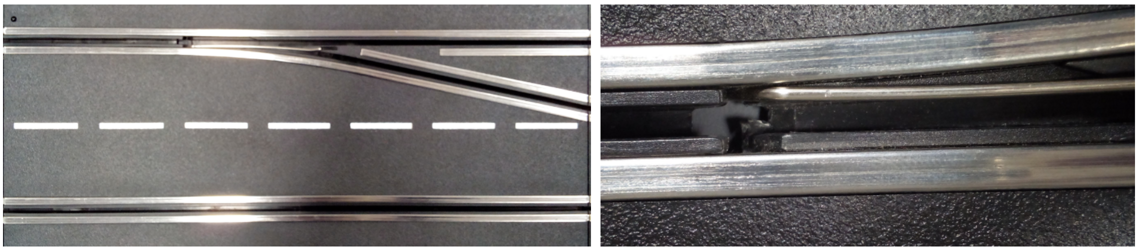

Figure 14: View of Carrera single-crossover section's point, and close-up of the point tip.

The Carrera tracks are made of rigid plastic which is hard to bend. There is a red clip used to hold the tracks together that can be seen protruding in figure 11. The clip can be pushed out of the track join either way, so occasionally the clips need to be moved from one side to the other when changing layout, but they result in a strong connection, compared to the Scalextric inbuilt clips. Losing those red clips can be quite easy—they are supplied separately, and they can be pushed out of the track completely. Once you see how it works this system is about as easy to use as the Scalextric one. The end bit of the metal rail protrudes and meets a hollowed connector to make electrical connection track to track, the same way as the Scalextric track. The metal is relatively thin, and the connector can bend or even snap if not treated correctly when connecting the tracks, as we learnt from experience.

The tracks are 198mm wide. This is noticeably wider than the Scalextric and SCX systems, and is described as being on a "1:24" rather than "1:32" scale, although it would be narrow track on the

1:32 scale, even without taking the edge guard/barriers into account. The slot is 8mm wide, also the largest of the three.

The Carrera lane-change track supplied in the starter set offers a single lane-change function as shown in figure 14. The lane changer's point blade is made of a piece of metal wire with its pivot point isolated from the rails. When lane changing, the lane changer sits on plastic which wraps inside the two rails as shown in the close-up. This design adds some complexity but ensures that the car goes smoothly along the track. If the point blade fails to make contact with the slot metal, a "dead zone" distance of 80mm would occur; in comparison with Scalextric, this is both shorter, and less likely to impact the car. Stalling was not a problem on switches in the Carrera system in our tests.

The Carrera set does not have an edge-guard accessory like the other systems, instead offering a set of clips and a thin plastic strip that is used to provide fences for the corners. While this is effective in helping the cars stay on the track, *it is so flimsy that it soon breaks*. Referring to figure 12, the red-white striped strip fatigues and breaks easily, and also slips out of the holding posts quickly. This is a cheap option, and one of the biggest drawbacks in the Carrera system.

4.3 SCX Track

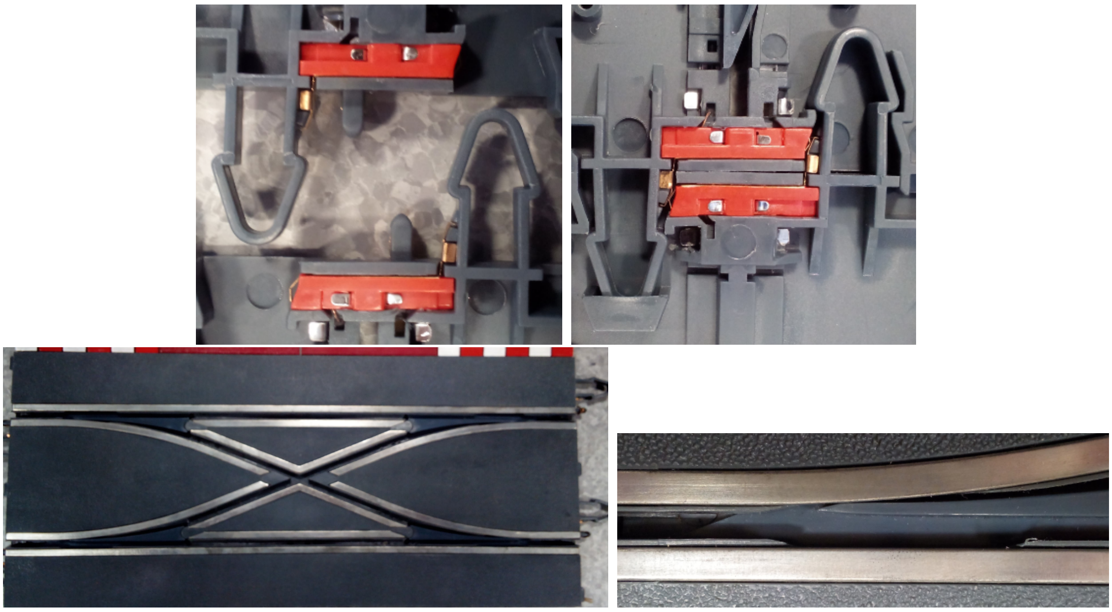

Figure 15: View of SCX track connection hardware open and closed, and a double-crossover section including close-up of the end of the point blade.

The SCX tracks are made from flexible plastic materials just like Scalextric tracks, but are lighter grey in colour. The SCX track is 160mm wide, slightly larger than the Scalextric system. The distance between the rails is 6mm. The arrow-shaped connector visible in figure 11 can be inserted into the next track piece with a gentle push. This design is more intuitive compared with the other systems because you do not need to remember what is "underneath", you simply pull or push. The tracks can be put together or taken apart in seconds yet there is reasonably strong connection. The metal rail end part has a thin copper band wrapped around it which makes contact with the other rail—refer to figure 15. Additionally, there is some copper on the side of the arrow shaped connector, and this contacts another strip on the correcponding receptacle. This gives redundancy to ensure that the two tracks are fully connected. While none of the systems gave any connection continuity problems for the duration of this study—some weeks—some of us can remember having this problem with older tracks, and some older Scalextric track was available in the lab for comparison. The rails showed corrosion, and connection was not reliable. This left us with a feeling of confidence in the durability of the SCX design.

The lane change track supplied in the set was a double-crossover "X"-shaped single section, resembling the Scalextric track. The first difference is that this one has points at all four intersections of the track, so it can be fitted and will work in either direction.[5] The track operates mechanically by spring systems, with no electronics in the tarck at all, refer to section 4.4. When lane changing, a "finger" on the car pushes the lane changer to the side and a spring pulls it back afterwards. The point blade itself is made of plastic and features a sleeved design similar to the Carrera tracks. The insulating nature means it has the chance of "stalling" the car as in the Scalextric system, though the problem was less pronounced as in the Scalextric system. The length of the potential "dead zone" is only 70mm, less than both the other systems, in spite of the fact that the point blade is not metal at all.

The SCX edge guard system, visible in figure 12, is easily the most robust. The red part is soft plastic, the barriers rigid and solid. This edge system was quite effective in keeping the cars on the track.

4.4 Track Switching

As a car approaches an intersection, some mechanism (electronic or mechanical) physically moves a guide arm that we call a "point blade" to steer the car in the right direction. How are the point blades made to do this?

4.4.1 Scalextric

The Scalextric lane-changer has a push-pull solenoid system. Two solenoids are used, one for each direction. The solenoids are controlled by a circuit housed in separate track section (in the case of curved single points) or housed at the beginning of an extended-length track piece (in the case of the double-crossover section). Refer to the disassembled example in figure 16.

The control circuit is powered from the track rails. Three-terminal voltage regulators are used to power the electronics and solenoids. The circuit uses optical sensors to determine the destination lane. The Scalextric cars have LEDs which emit signals as they pass over the track. Freewheel protection diodes for the solenoids, photoreceptors, etc., can be seen on the board. The cars signal a desire to change lanes by inverting their ID signals transmitted by the car-mounted LED. A duty cycle greater than 50% seems to request a change. Figure 17 shows the signals transmitted.

4.4.2 Carrera

The Carrera lane changer uses a similar system to that of Scalextric. The guiding arm is moved by a solenoid that is controlled by a circuit that reads an optical signal. The Carrera cars also have an LED which emits a signal as the car passes over the track. The optical sensors read this signal which is then interpreted by the processor (an Atmel chip). The circuit then powers the solenoid if a lane change is to occur. The difference lies in the use of a single solenoid. The Carrera cars reset the point blade to its original position (straight, no change) after every lane change by a physical interaction of the car on the track. A small lever is hit by the guide blade of the car when the car passes over it, resetting the point blade arm position. This eliminates the need of a second solenoid for return.

[5] This reversibility is ironic, as the SCX system is unidirectional, whereas the Scalextric system will allow a car to be driven both ways around the track, even though points will not work in the reverse direction.

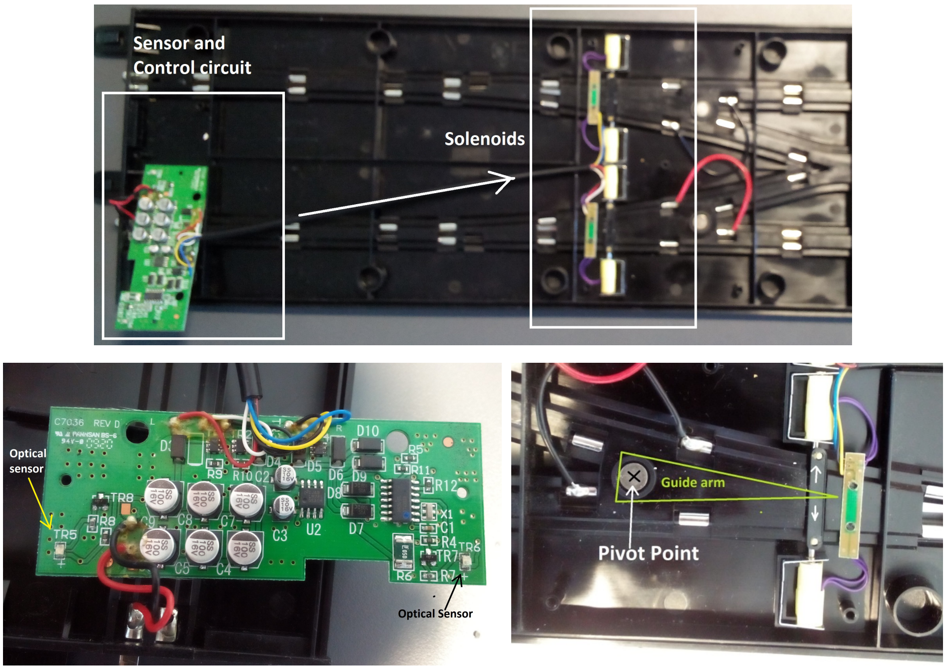

Figure 16: The Scalextric point mechanism with close-ups of the control PCB and actuators.

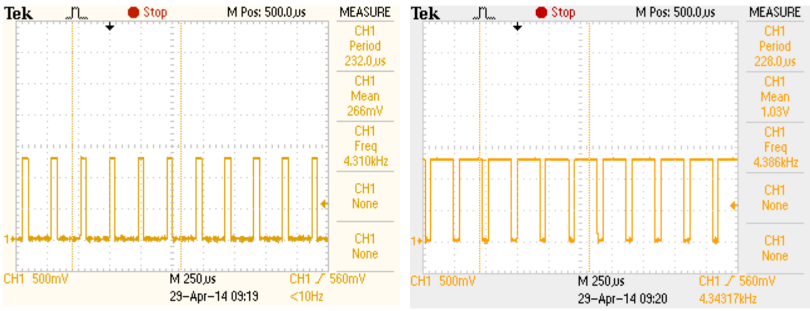

Figure 17: The signals received by the track for the same Scalextric car in normal and lane-change, state respectively.

Figure 18 shows the workings of a switch track section. The Carrera lane changer uses less electronics components.

4.4.3 SCX

SCX lane changer runs purely on mechanical operations. The cars have a special plastic piece which extends out when a lane change is desired—refer to figure 19 and for more detail about the car's actuator see figure 7. This "finger" piece catches on a recessed ramp of the point blade visible in the view from below in 19. The switch blade then moves about its pivot, guiding the car to the opposite lane. A spring is in place which pulls the guiding arm back to default position once the car transits the switch.

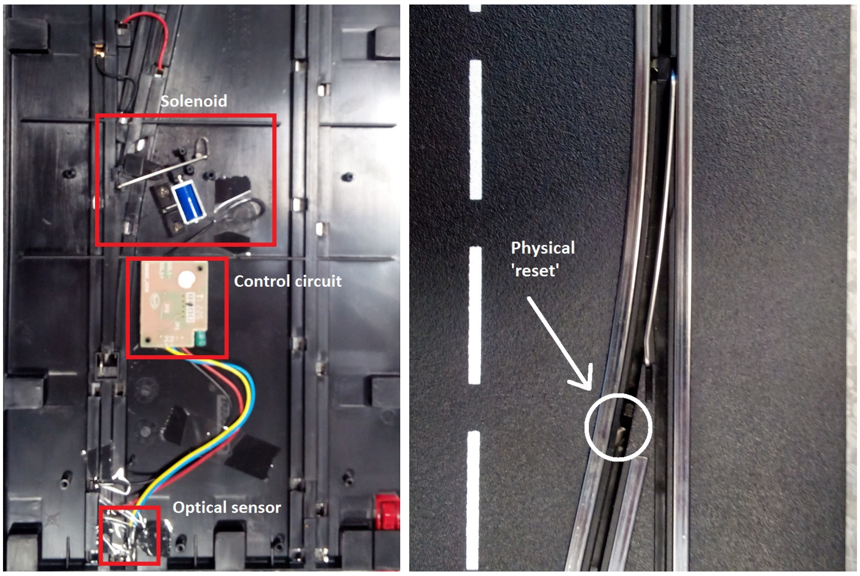

Figure 18: The Carrera switch track mechanism.

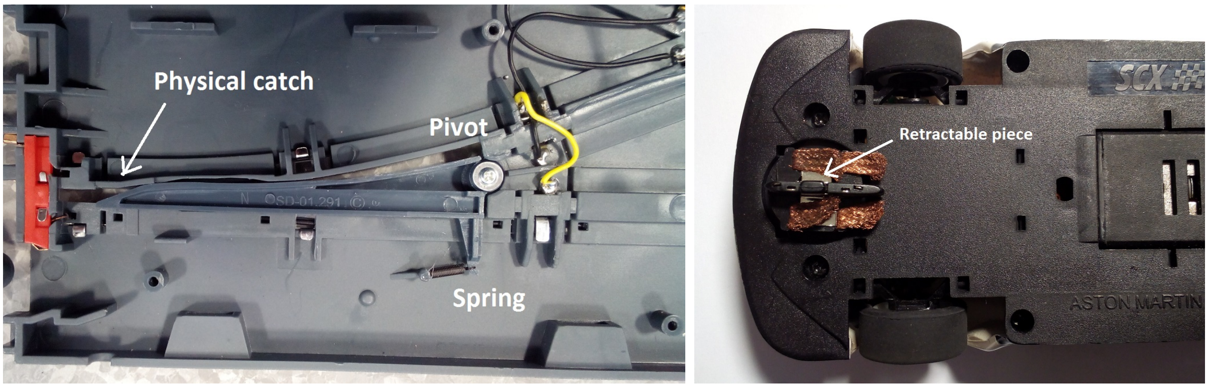

Figure 19: The SCX switch track mechanism and the position of the finger that protrudes from the car guide blade.

5 The Hand Controllers

We will start by describing the hand controllers provided by each system, then discuss the main control box ("hub") and its usability. Figure 24 shows the three different controllers. All three brands have colour-coded the hand controls, but there is a strong temptation to write car address numbers on the controllers unless your selection of cars happens to correspond to the controller colours (as they roughly did, though this was likely a coincidence).

5.1 Scalextric Hand Controller

The Scalextric controller is a very traditional pistol style shape with a trigger for the throttle operated by the index finger and two buttons on the back operated by the thumb. There is a strong helical spring that provides solid resistance to the accelerator-finger, so the trigger has a high "weight" and a quality feel to it. The controller is quite light and is fits nicely in your hand. It is an ambidextrous design. The rear buttons, which control the brake and the lane change functions, feel mushy and do not have any tactile feedback to them. They feel very cheap and unsatisfying to press. The cable

Figure 20: The hand cotrollers provided with Scalextric, SCX, and Carrera sets respectively.

that attaches the controller to the hub is 2-core, about 1.6 m long, and uses a 2.5mm audio plug and jack. It is a plain cable (not coiled) and is a little stiff feeling. The lack of coiling means that the cable has a tendency to fall onto the track and get in the way of the cars.

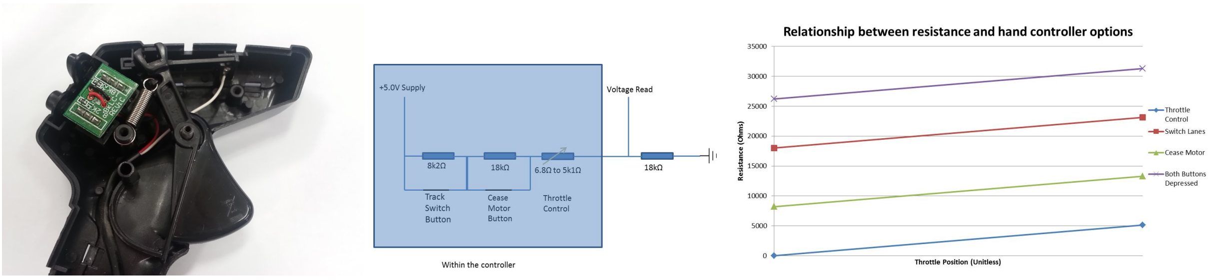

Figure 21: Details of the Scalextric hand controller. The mechanical layout at left shows the linear potentiometer element. The circuit diagram and the resulting resistance as a function of trigger position and buttons depressed appear middle and right.

The trigger moves the handle on a linear potentiometer and slides it back and forward. Refer to figure 21. The potentiometer is wired in series with two switches each of which is wired in parallel with a resistor. The circuit is also shown in figure 21, along with the resistance across the connecting wire that results. The switches are normally closed so when either button in pressed the overall resistance increases. The value of resistors wired to each button is different. This creates separate ranges of resistance values for various button combinations and allows the controller to use a two wire interface to the controller hub. The hub can correctly identify applied controls to the controller, by analysing the overall resistance via a resistive divider.

5.2 SCX Hand Controller

The SCX controller is very similar in style to the Scalextric controller. The main difference is that it only has one button on the rear as it lacks the brake function. The handle is slightly rubberised giving added grip in the hand. The throttle trigger is quite soft and has a lightweight feel. The controller is quite comfortable to use and has an ambidextrous design. The lane change button has a very noticeable tactile click to it which is quite satisfying. The cable is a 4-core coiled type with a phone-style plug and jack that stops it from falling onto the track. The overall cable length is about

1.6 m, falling to about 0.5 m when coiled. See figure 22. Note that the small coil spring that normally resides behind the hub of the trigger is not present in the figure.

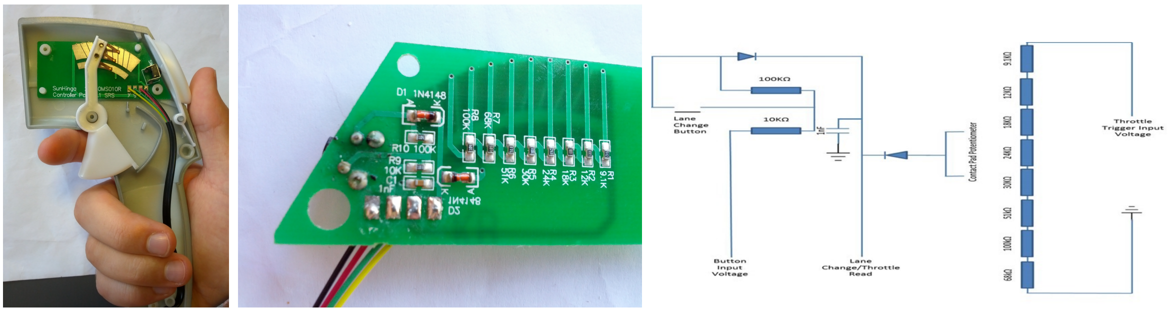

Figure 22: Details of the SCX hand controller. The mechanical layout at left shows the wiper connected to the trigger. The back of the PCB carries components, and the circuit diagram is shown at right.

The throttle trigger is attached to (copper?) metal contacts. These scrape along exposed (gold plated?) metal segments on a PCB. On the other side of the PCB there are a number of components. As the throttle trigger is pushed and released, the total resistance of the path varies and this is used to set the speed of the car. The circuit appears in figure 22.

Electrically, the SCX controller provides the most unique circuit design out of all three controllers. It uses square wave signals that have opposite phase (and different duty periods) on two separate inputs of the controller. Referring to the circuit, the "Throttle Trigger Input Voltage" and the "Button Input Voltage" are alternately driven high. Both throttle position and switch lane detection are read from the same output connection. Protection diodes are used to prevent both potentiometer and button output voltages from interfering with the other half of the circuit, so that button and trigger are alternately polled. The throttle position is sensed knowing that a level of 3.5V is applied to a resistive divider, and the trigger sets the divider ratio. This takes approximately 22 mS. The cycle of reading button and trigger takes 50 mS. Although this requires four instead of Scalextric's two connecting wires, we speculate that it might afford the ability to use an ac waveform to improve immunity from interference. Alternately, it may be simply inefficient electronic design, since two wires could be separately used for sensing each of trigger and button.

Over the course of using the controller the throttle trigger can become unresponsive (or act erratically). This manifests itself in jerky car movement, akin to what is experienced if dust collects on the pickup braids, and could cause problems that a user might find hard to diagnose. It has been found that cleaning the contacts (the exposed metal on the PCB) resolves this. Curing this requires the controller to be dismantled periodically to ensure a reliable and fun experience. We postulate that there is some surface corrosion arising through the use of incompatible metals in the wiper-PCB system. When first opened, the controllers were found to have a (petrolium?) grease spread on the PCB contacts. When this was cleaned off with isopropyl alcohol responsive operation was restored. *This is a serious design issue that potentially could ruin the experience of a non-technical user.*

5.3 Carrera Hand Controller

The Carrera controller is quite different from the other two. Instead of a trigger for the throttle there is a plunger on the top that is activated with the thumb. The lane change button is located under the index finger where a trigger would normally be. This layout can cause confusion as most people are accustomed to having the throttle control under their index finger. Refer to the first image in figure 23 for a view of the intended grip. The controller itself is quite comfortable to hold as it is moulded to fit the contours of your fingers. The plunger has a low weight to it considering that it is activated with the thumb (much stronger than a finger). The overall design is very compact and is also ambidextrous. The lane change button has a tactile click to it but it is not very satisfying as it has a lot of travel for a switch. It also sits very high on the finger (close to the first knuckle) which makes it a little difficult to press. The cable is a tightly-coiled 4-core design with a phone-style plug and jack similar to the SCX system. The tightness keeps it out of the way of the cars. It extends to about 1.6 m.

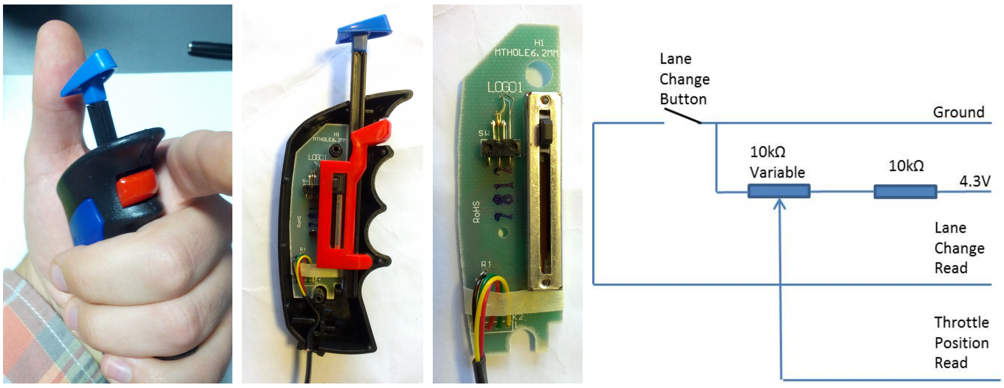

Figure 23: Details of the Carrera hand controller. The style of grip appears at left. The mechanical layout of the open unit shows the button (red) and switch contacts. The PCB carries a commercial slider potentiometer. The circuit diagram is shown at right.

The shell of the Carrera controller is made in halves from a hard plastic. It is quite solid and feels as if it would be resistant to abuse. The cable is anchored to the controller by means of an S-shaped path inwards, but does not have any strain relief mechanism. This could result in the cable slipping where it enters the controller and breaking if tugged forcefully. Although black-on-black, this is visible in the second image in figure 23.

The throttle plunger mechanism is weighted by an extension spring. The linear action of the plunger moves the wiper of a linear potentiometer. The lane change button is a large plastic mechanism that pivots and pushes a small switch. It is the switch that provides the weight and the tactile click on the button.

Electrically, the controller uses a four wire interface. The red wire is for the 4.3 V DC in, the black one is for ground, while the yellow and green are outputs for the throttle potentiometer and lane change switch respectively. All components are mounted on a single sided PCB that extends most of the length of the controller. The only components on the board are the switch, the linear potentiometer and a through-hole 10kΩ resistor.

6 Controllers

In each system there is a main control box that supplies power to the tracks, reads the hand controllers, converts the driver instructions into digital data, and broadcasts this out to the cars on the track. The three control boxes, variously called "hubs", "black boxes" or simply controllers, are pictured in figure 24.

Figure 24: The main controllers for Scalextric, Carrera and SCX systems.

6.1 Scalextric

The Scalextrix controller hub is very simple. It consists of a DC power input, four controller inputs, four programming buttons and an LED. This makes it very easy to use. To program a car to a controller channel you simply place the car on the track (by itself) and hold the corresponding programing button down until the LED flashes. Thereafter the controller plugged into the jack nearest a given numbered button controls the car programmed to the address written on that button. It is intuitive and does not require the user to remember any obtuse key-press sequences.

Elecronically, the Scalextric controller hub takes a 15 V DC power input which is supplied by an external power pack supplied with the set and presumably customizd for the country of sale. On the PCB, a 7805 linear voltage regulator supplies 5 V to a microcontroller and other circuitry, while the 15 V is used to power the track. The microcontroller used is a Microchip PIC16F819. This is an 8-bit microcontroller capable of up to 5 MIPS, has 3.5 KB of program memory, and one PWM output. In large quantities it is available for about US$2.20 per chip. To encode data on the track an H-bridge is used, as the Scalextric system provides AC power—refer to section 3. This bridge is powered by the 15 V rail and consists of four LR9343 mosfets. Each pair of fets has a heatsink. There is also a heatsink on two S5AC high-current diodes.[6] There are also two 100mΩ resistors in parallel to sense the current flowing into the track. Overall the PCB in the Scalextrix hub is quite bare. The only I/O is the four controller ports, the DC power in and the track output. There is also one button for each controller channel and a green LED to indicate the hub is on. The only other interesting section of the board is the track output which includes five inductors along with some capacitors. This is to attenuate high frequency signals going to the track for compliance reasons.

[6] These two diodes are strangely arranged in series, and it is not clear what their purpose might be. The only explanation for their being in series is that they are arranged like this to use use the same heatsink as is used on pairs of the fets, which would not be possible if they only had one diode. They may protect the remainder of the circuitry from spikes and surges on the bridge connections that go to the track.

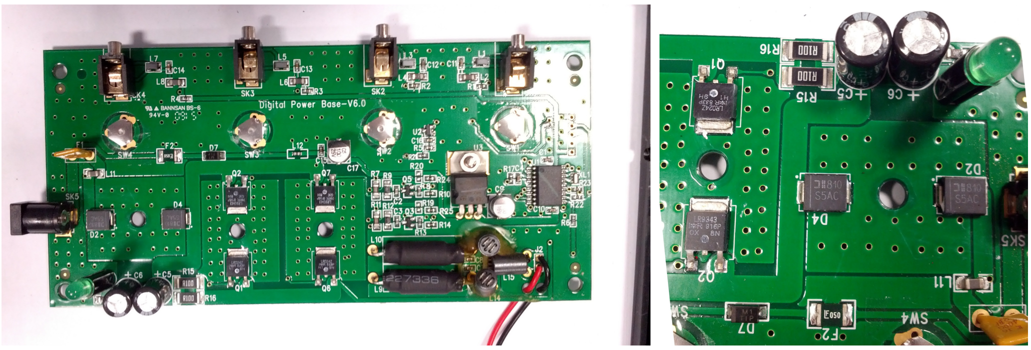

Figure 25: The main PCB in the Scalextric hub, pictured with heatsinks removed from the MOSFETs and power diodes. Close-up shows the diodes and current sense resistors, and one pair of MOSFETs. The 5mm holes between the diodes and FETs allow for bolts to hold heatsinks in place. The mustard-coloured component at lower right of the close-up image is a soldered-in thermal fuse.

6.2 SCX

The SCX controller provides more functions compared to the Scalextric one, but is still quite simple to use. We thought that the SCX user interface was perhaps the best of the three. It has three controller ports with an LED for each. The LED turns from yellow to green when the control hub detects that a particular controller is plugged in. It also has four buttons, one to turn the car headlights on and off, one to program the cars to a controller channel, one to start a race (only has an effect if the appropriate add-ons are connected) and the last is for setting the maximum speed of the cars. See figure 24. Programming a car is easy. You simply place the car you wish to program on the rack, hold the programming button until the light blinks, then push the lane change button on the hand controller with which you wish to control the car. This is reasonably intuitive once you remember that the hand-controller buttons are involved. The other basic features of the hub (such as headlight control) are also very easy to use as they each have their own button and indicator.

Electronically, the SCX controller hub takes an 18 V DC power input supplied by an external power pack. A 3.3 V linear regulator supplies power to the micro controller and other control circuitry. The microcontroller is a Freescale MC9508 operating at 4 MHz. This is an 8-bit microcontroller that costs about US$2.30 in large quantities. It features 60 KB of flash memory and 54 digital I/O pins. To encode data on the track, two D442 mosfets are used. SCX essentially runs a DC power supply, refer to section 3. Between the fets is a 56Ω, 5 Watt resistor used to pull the voltage on the track down when the FETs are off. There are three power connectors on the board that are wired in parallel. This is so that when track add-ons are connected, additional power supplies can be connected to provide the required current to the track.[7]

6.3 Carrera

The Carrera controller/hub has a multitude of features.

Race mode Race mode initiates a controlled start signalled by a series of beeps accompanied by a string of LEDs illuminating sequentially. Also, a player who makes a false start is identified.

Pace car This allows any car to be set up to run at a constant set speed with no ongoing user

[7]These additional power connectors are a little surprising, as power is essentially available anywhere there is track, by definition. This reinforces our suspicions that the SCX designers were more mechanically than electronically-oriented in their thinking.

interaction required. This is particularly handy for practice, and means that four cars can be running even though only three hand controllers are supplied in the set.

Car lights The headlights on each car can be individually turned on or off

Set speed Allows the maximum speed of all the cars to be set (one speed for all cars)

Braking level Allows the braking-effect level of all the cars to be set (one braking level for all cars)

The procedure to program each of these features into the cars requires a series of lane change button presses and lifting the car off the track. For example, to enable the pace car function, the user has to place a car on the track, press the lane change button twice, lift the car off the track for a second or so, place the car back on the track, press the lane change button four more times, set the desired car speed with the throttle plunger and then press the lane change button once more. The other functions require a procedure of similar complexity to be followed. Without referring to the manual, it can be difficult to remember the procedure for each of the functions. One of the unique features of the Carrera hub is that it has an inbuilt speaker. It uses this to signal the race start when using that feature and to indicate a short circuit on the track. There is the option to turn the speaker off via a switch on the side of the hub.

Electronically, the Carrera controller hub takes 14.8 to 18V DC power, supplied again by an external power pack. The power connector is a board edge connector that can bee seen to the right of the PCB, shown in figure 26. An L7805CV linear voltage regulator is used to provide a 5 V rail used for the microcontroller and hand controllers. The microcontroller used is an Atmel ATMEGA16A which is an 8 bit chip running at 8 MHz giving it maximum performance of 8 MIPS. It features an 8-channel 10 bit ADC, 32 digital I/O pins and 16 kB of flash. In large quantities they are available for US$2.83 each. To encode the data onto the track a D417 mosfet is used with a high power 120Ω pull down resistor. This design requires no heat sinks.

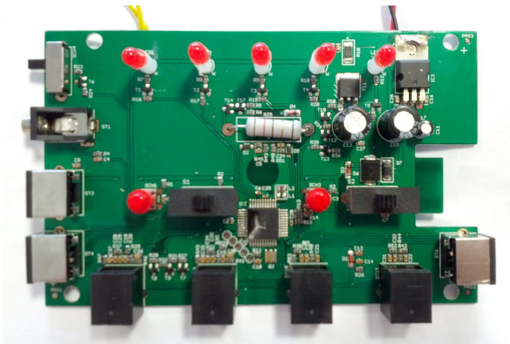

Figure 26: The main controller PCB in the Carrera system. Note the array of 5 LEDs across the top of the circuit that are used to count down a race start or signal an alert. The power connector comes in from the right.

7 Conclusion

The three systems expose enormous design differences. Each has its own shortcomings. The most prominent shortcoming of the Scalextric system was the "point stalling" problem. The most prominent shortcoming of the SCX system was the hand controllers and their need for frequent maintenance to prevent erratic operation. The Carrera track was its main disappointment, the cheap feel and the barriers that soon fail, reducing the driving pleasure.

We collectively felt that the Carrera system was the best of the three, although the build quality was lower, and the track felt especially cheap. We liked some aspects of the SCX system, especially the relatively low cost of switch sections and the build quality of cars and track. We were left with the impression that the SCX system, while mechanically ingenious, was less versatile and the hand controller mechanically and electronically disappointing. The Scalextric system has the advantage of using the tried-and-true DCC technology, and offers a flexible design. Nevertheless, we felt that the Scalextric system was not refined and improved as it might be. We often found ourselves asking why this or that obvious advantage had not been incorporated into the product.

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