Speed and Directional Control of American Flyer Trains

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http://doerry.org/norbert/train/AFtrain.htm
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History
1. **Introduction**¹

The purpose of this document is to explain how the electrical and electronic components typically encountered with American Flyer trains work. In particular, this document concentrates on describing how the components work together to implement speed and directional control. The document also discusses how speed and directional control can interact with other components such as sound generators and action cars. Where possible, actual oscilloscope displays have been included to show the voltage and current waveforms under different operating conditions.

Please contact the author if you find any errors. Also, feel free to suggest improvements or additions to this document. Revisions will be produced as needed to correct errors and add more material.

1.1 **Definitions**

**Rotor:** the part of a motor that rotates. Also may be called the rotor assembly.

**Stator:** the part of a motor that is stationary. Also may be called the stator assembly.

**Field:** The part of the motor that establishes a magnetic field. The magnetic field can be created by a permanent magnet, or by a coil of wire. The field usually contains laminated steel to direct the magnetic field to where it will interact with the armature. The field can reside either on the stator or the rotor.

**Armature:** The part of the motor that carries current through a conductor to interact with the magnetic field created by the field to create a magnetic force. The armature winding usually contains one or more coils of wire around laminated steel. The armature winding can reside either on the stator or the rotor, complimentary to the location of the field. While a field can contain a permanent magnet, an armature will always have a coil.

**Commutator:** A commutator is a type of switch for controlling the current through the coils of the armature. For most simple motors with the armature on the rotor, the commutator is a rotating mechanical switch that consists of strips of copper connected to the armature windings that slide against carbon brushes. The commutator is designed to electrically connect the proper armature coils to maximize the electromagnetic force that will cause the rotor to rotate in the desired direction.

**E-unit:** An E-unit is a device, either electro-mechanical as with the original American Flyer e-units, or completely solid state with modern ones, used to control the direction of the engine.

1.2 **System Description**

With the exception of battery powered trains, the powering of an electric train motor can be broken up into two parts: supplying power to the track, and converting the power picked up from the track (via wheels or pickup "shoes") to the form needed by the motor to achieve the desired direction and speed.

1.2.1 **Powering the Track**

For most American Flyer trains, power is supplied to the track directly from an AC transformer as shown in Figure 1. The voltage supplied varies from about 7 volts to about 16 volts based on the position of the

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¹ *American Flyer* and *A.C. Gilbert* are trademarks of Lionel Trains, LLP. This document is neither authorized nor approved by Lionel Trains, LLP.
speed “throttle” knob. The higher the voltage applied, the faster the train operates. Directional control is normally accomplished by briefly interrupting the flow of current by turning the knob to the off position, then reapplying power. Some transformers have a button that will interrupt the power when pressed, thereby eliminating the need to move the knob to off.

A third "post" on the transformer is available to provide a constant voltage between about 15 and 16 Volts as compared to the "base post." This post is used to power accessories, or action cars through a pickup rail.

![AC Transformer directly powering the track](image)

For trains that are designed for DC operation, a DC power source can be connected as shown in Figure 2. As with the AC transformers, the knob controls the voltage and the higher the voltage, the faster the train travels. For DC operation though, the maximum voltage is generally higher, up to 21 volts (Note that some DC engines are designed for lower voltage - ensure the DC power source is compatible with the DC engine). For trains that are designed for DC operation, a reverse switch on the DC power source will reverse the polarity of the power applied to the tracks (which rail is + and which rail is -). For these DC engines, the polarity signals which direction the engine should move. As shown in Figure 3, these DC power sources typically also provide two posts for supplying a constant AC voltage to accessories.
Engines designed for DC operation can be powered from an AC transformer if a rectifier is inserted between the transformer and the track as shown in Figure 4 and Figure 5. These rectifiers convert the AC into DC and then incorporate a reverse switch to enable the operator to reverse the polarity of the DC power applied to the track.

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Digital Command Control (DCC) is another method for powering the track and signaling to the engine the intended speed and direction. With DCC, the light weight hand throttle can be moved around the layout and still control a number of engines and other devices. Some hand throttles are wireless and hence do not need to be directly connected to the Command Station. The Command Station / Booster encodes digital commands in the track power that are used by a decoder on the engine to determine the engine direction and speed. See Figure 6.

3 Instructions for Assembling and Operating American Flyer 3/16” Scale Trains and Equipment, Developed at the Gilbert Hall of Science, 1949.
Trainmaster Command Control (TMCC) is a proprietary train control system produced by Lionel and incorporated in some recent American Flyer engines. As shown in Figure 7, a constant voltage (typically AC) is provided to the track. The Command Base couples a signal onto one of the track rails which is picked up by the engine. A TMCC decoder on the engine receives and executes the commanded speed and direction.

1.2.2 Getting Power from the Track to the Motor
The train engines receive power from the track via metal wheels and/or electrical pickup shoes. The power can either be directly applied to the motor, or it can be "conditioned" to match the needs of the motor in order to implement the commanded speed and direction. The "conditioning" can be as simple as a reverse switch or rectifier (Figure 8), or as complex as an electronic digital control, electro-mechanical E-Unit or electronic E-unit.
Figure 8: Rectifier and Reverse Switch in a tender

Figure 9: 4 position and 2 position Electromechanical E-Units

Figure 10: Electronic E-Unit (Lionel American Flyer 6-48005)
2. Motors

Most toy train motors work by turning on and off as well as controlling the direction of current through the armature windings (typically via the commutator) to keep the magnetic fields on the rotor and stator out of alignment. By having the magnetic fields out of alignment, a torque is produced that will rotate the rotor to align the two magnetic fields; as soon as the fields are aligned, different sets of coils are energized to put the two fields back out of alignment. The way in which this is accomplished differentiates the different types of motors.

2.1 Universal Series Wound Motors

Most American Flyer trains use a universal series motor (or simply a "universal motor") having both field windings and armature windings. These motors will operate either on AC or DC power. A universal motor has a wire wound field coil on the stator, and an armature on the rotor. The armature typically has 3 (as with the American Flyer motors) or more coils. Current through the armature windings is controlled via a commutator and its associated brushes. (See appendix B) The armature (via its brushes) and the field are connected in series. The direction of rotation of the motor is determined by which wire end of the field winding is connected to the armature (the other end of the field winding is connected to the power supply, likewise for the other end of the armature). Direction of rotation does not depend on the direction of the current, hence the motor will work with either ac or dc power. To change the direction of rotation, the field winding (or alternately the armature winding) connections must be reversed. (The American Flyer E-unit does precisely this)

The brushes are usually made out of a graphite / carbon based material and held in contact with the commutator with brush springs. The brushes are often held in place with a brush bracket assembly that many times also serves to hold the bearing supporting one end of the rotor.

In the parts list associated with many of the American Flyer engines, the rotor is also known as the armature assembly. Similarly, the stator is called either the magnet assembly, or the field assembly. Figure 11 shows the different parts of a universal motor for an American Flyer steam engine. Figure 12 shows a universal motor mounted on an engine chassis.

For the American Flyer motors, the voltage drop across the field winding will be much less than the voltage drop across the armature winding (Typically the voltage across the field is only a few volts at maximum track voltage). Consequently, many of the American Flyer steam engines with the E-unit in the tender connect the smoke box and the headlight across the armature winding so that only four wires (2 for the field windings and 2 for the armature windings are needed to connect the tender to the engine. A 5th wire is needed if full track voltage is desired for the headlight and smoke box.
Figure 11: Parts of an A.C. Gilbert universal series wound motor for a steam engine.

Figure 12: Open frame motor mounted on train engine chassis

Figure 13: Open Frame motor for diesel engine
2.2 Open Frame DC Permanent Magnet Motors

An open frame DC Permanent Magnet Motor is similar to the universal motor, except the field winding is replaced with a permanent magnet. As a consequence, the direction of rotation is determined by the direction of current flow through the armature (via the commutator/brushes). Hence these motors will not work properly when connected directly to AC power.

The armature windings of a DC permanent magnet motor typically use more turns of thinner wire than an ac motor. One should not consider the rotor assemblies of open frame DC permanent magnet motors and universal motors to be interchangeable.

2.3 DC Can Motors

The only difference between the DC Can Motor and the Open Frame DC Permanent Magnet Motor is the method of construction. DC Can Motors are completely enclosed with the bearings for the rotor incorporated into the "Can" housing.

Figure 14: Cam motor for GP-9 diesel engine (Lionel American Flyer 6-48005)
3. Track Power

The waveforms shown below were measured for an American Flyer Atlantic engine with headlight, smoke unit, and a 4 position E-unit locked in the forward position. The engine was pulling a box car, gondola, tank car and caboose. The transformer was an American Flyer model 4B 100 watt transformer set for maximum voltage. A 10,000 uF filter capacitor was used for the filtered DC option. Current was determined by measuring the voltage across a 1 ohm resistor in series with the track.

3.1 AC variable voltage

The traditional method for powering most American Flyer engines is directly from a variable voltage AC transformer. The voltage varies from 7 volts AC to about 15 or 16 volts AC depending on the position of the throttle knob. As seen in Figure 15, the track voltage has a sine waveform with a minimal amount of distortion. The current waveform, shown in Figure 16, is not completely sinusoidal, but is relatively close. As the waveforms deviate from sine waves, the amount of energy converted to heat in both the transformer and the motor increases.

3.2 DC variable voltage

DC power is generally created by rectifying AC power and then possibly filtering the power with a large capacitor. This section describes three different ways of producing DC power: Full wave bridge rectification, half wave rectification, and filtered DC.

3.2.1 Full Wave Bridge Rectified AC

A Full Wave Bridge Rectifier is a device consisting of 4 diodes connected as shown in Figure 17. A diode only allows current to flow in the direction of the arrow. When conducting current, a diode has a voltage drop of about 0.6 volts. The bridge rectifier connects the more positive of the two AC inputs to the DC + output, and the more negative of the two AC inputs to the DC - output. The resulting voltage waveform at the track is shown in Figure 18: The negative half of the input ac waveform is flipped so it too is positive. While the resulting waveform is not a pure constant voltage DC, the polarity of the track voltage is always the same. To reverse the polarity of the track, a double pole double throw (DPDT) switch is configured as a reversing switch as shown in Figure 19. The current waveform for the track power is shown in Figure 20. Note that while the current is not constant, it does not change polarity.
As shown in Figure 21, the transformer current is an AC waveform, but it does exhibit more distortion than when supplying AC to the track.

The current rating of the rectifier should be based on the rating of the transformer. The rectifier should survive when supplying current equal to the maximum current the transformer can supply without tripping its circuit breaker. Most transformers have a circuit breaker that trips slightly above the rated current. The rated current can be approximated by dividing the power rating by the maximum voltage (typically 15 volts). I recommend the voltage rating for the rectifier should be at least 100 volts to ensure the rectifier survives voltage spikes.

<table>
<thead>
<tr>
<th>Transformer Rating (Watts)</th>
<th>Rectifier Minimum Current Rating (amps)</th>
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<tbody>
<tr>
<td>50 or less</td>
<td>5</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>75</td>
<td>8</td>
</tr>
<tr>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>125</td>
<td>10</td>
</tr>
<tr>
<td>150</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 17: Full Wave Bridge Rectifier Schematic
Figure 18: Track Voltage Waveform: Full Wave Bridge Rectified

Figure 19: Circuit Diagram for Full Wave Bridge Rectifier

Figure 20: Track Current: Full Wave Bridge Rectifier

Figure 21: Transformer Current: Full Wave Bridge Rectifier
3.2.2 Half Wave Rectified AC

A half wave rectifier consists of a single diode that allows current to flow in only one direction. The resulting track voltage is shown in Figure 22. The diode is on during the entire positive half of the waveform, and dips below zero for a short time to "drain" the energy stored in the magnetic fields of the motor windings (motor inductor current). When the current through the diode is zero, the diode turns off and stays off until the input voltage waveform becomes positive again. To change the polarity of the track, a reversing DPDT switch is used to reverse the direction of the diode as shown in Figure 23. This circuit has the advantage that the base post of the AC transformer is connected to the base rail of the track at all times, allowing action cars to work normally. The disadvantage of this circuit is that the transformer current is definitely not sinusoidal (see Figure 24) and results in greater losses in both the motor and the transformer. If this circuit is used, I recommend avoiding overheating the transformer by using a transformer rated at least 100 watts for a single motor engine and at least 150 watts for a dual motor ALCO.

As with the bridge rectifier, the current rating of the diode should be based on the power capability of the transformer. Use Table 1 as guide for selecting the diode current rating. The reverse voltage rating of the diode should be at least 100 Volts.

![Figure 22: Track Voltage: Half Wave Rectifier](image-url)
3.2.3 Filtered DC

A closer approximation to constant voltage DC for the track voltage (Figure 25) can be obtained by inserting a capacitor across the output of the bridge rectifier as shown in Figure 26. Capacitors store energy and can be charged and discharged very rapidly. In this application, the capacitor charges when the rectified AC waveform is near its peak, and discharges to fill the valleys between the peaks of the rectified AC. The resulting track current used by the engine is also nearly constant DC as shown in Figure 27. On the other hand, the current provided by the transformer (Figure 28) is AC, but shows strong positive and negative pulses when the capacitor is charging.

An electrolytic capacitor is normally used in this application. For the several amps of current used by the motors, a capacitor with a capacitance of about 10,000 micro-farads or more should be chosen. The voltage rating of the capacitor should be at least 50 V to ensure its reliability in the presence of voltage spikes. Electrolytic capacitors of this rating are polarized, which means that one of its sides must always have a positive voltage with respect to its other side. This means that the capacitor should be connected across the rectifier output with the correct polarity, and before the reversing switch determines the polarity applied to the track.
Figure 25: Track Voltage: Filtered DC

Figure 26: Circuit Diagram for Bridge Rectifier with Filter

Figure 27: Track Current: Filtered DC

Figure 28: Transformer Current: Filtered DC
3.3 Pulse Width Modulation

Pulse Width Modulation (PWM) is a technique for controlling the average voltage through pulses of power. The average voltage is calculated by multiplying the "on" voltage by the fraction of the time the voltage is "on." PWM has the advantage of being easily controlled by a computer or microcontroller. With suitable power transistors and driver circuits, PWM can result in very low losses.

Figure 29 is an example of a test circuit for demonstrating PWM. A 20K variable resistor is used to vary the "on" time relative to the "off" time. When the "Gate Signal" is grounded, the output MOSFET turns on and applies the "on" voltage to the motor. This circuit was used to create the graphs in Figure 30. Note that at low speeds, the "on" voltage has a short duration compared to the "off" condition. Conversely, at high speeds, the "on" has a long duration compared to the "off" condition.

As shown in Figure 31, the track current has more of a DC characteristic due to after the transistor turning off, motor inductor current continuing to flow through the reverse biased "free wheeling" diode connected across the output as shown in Figure 29. The current provided by the rectifier however, does show the PWM characteristic as shown in Figure 32.
Figure 30: PWM waveforms (Top (orange) gate signal; Bottom (blue) motor voltage): (a) slow; (b) medium-slow; (c) medium fast; and (d) fast for unloaded Casey Jones universal motor with a rectified field.

Figure 31: PWM Track Voltage and Track Current for (a) Medium, and (b) Fast speeds
3.4 Fixed Voltage (AC or DC)

It is also possible to apply a fixed AC or DC voltage to the track and use some other means to communicate train direction and speed. For many engines, DCC can also be thought of as a fixed voltage of high (variable) frequency AC.
4. **Communicating Direction**

The following sections describe how an engine can be configured to respond to different methods of communicating direction.

4.1 **Fixed Direction (Forward only)**

In some cases, it may be desirable to have an engine only operate in the forward direction.

For universal motors, this can be accomplished by hard wiring the field coil and the armature in series such that the engine always goes forward. One end of the field coil is attached to one of the brushes for the armature. Track power is applied to the other end of the field coil and the other brush.

For DC motors, the easiest way is to use a bridge rectifier. The AC inputs are connected to the track pickups, and the DC outputs are connected to the DC motor in the polarity needed for the train to go forward. If desired, a filter capacitor can be placed across the DC output of the rectifier. This capacitor should be rated at least 50 Volts with a value greater than 1000 uF.

4.2 **Manual switch on engine**

If remote control of the trains direction is not required, a DPDT switch (either toggle or slide) mounted on the engine can be used to determine the engines direction.

For universal motors, the field winding is connected to the input of a reversing switch circuit (Figure 33). The output of the reversing switch circuit is connected in series with the field coil. One of the output connections of the reversing switch circuit is connected to the field coil. Track power is applied to the other reversing switch circuit output connection and the other brush.

DC motors, the inputs to the reversing switch circuit are connected to track power and the outputs of the reversing switch circuit is connected to the motor.

![Figure 33: Reversing Switch Circuit](image)

4.3 **Time Sequence (American Flyer E-Units)**

The original American Flyer E-Unit (Figure 9 on the left and Figure 34) consists of a drum that rotates 1/8 of a revolution each time power is applied. This is accomplished by an electromagnetic actuator connected directly to the power pickups. This actuator pulls a pawl down on a sprocket attached to the drum, causing the drum to rotate 1/8 of a revolution. The surface of the drum has two copper patterns that if flattened, would look like those in Figure 35. Two sets of copper "fingers" make contact with the drum surface. As the drum rotates with each application of power, the field coil is first connected for operation in one direction, then disconnected entirely, then connected for operation in the other direction, and then disconnected entirely again. This pattern is repeated as the drum rotates.
Figure 34: 4 position E-Unit with top set of fingers removed to reveal drum below.

Figure 35: Gilbert American Flyer 4 position E unit operation

A DC motor can also use the Gilbert E-Units. The only difference is that the E-unit is wired as shown in Figure 36.
The later 2 position E-Unit (Figure 9 on the right) uses a solenoid that toggles a switch in one of two direction (Figure 37). This switch is configured as a reversing switch which alternately switches the connection of the field coil (Figure 38). When the power is off, the solenoid plunger is in the down position. The drum is shaped so that when power is applied and the solenoid plunger rises into the solenoid coil, the solenoid plunger also pulls up on the drum to rotate it slightly and change its position. Only two fingers are used which connect to the field coil. The drum pivot points are also used for electrical connection to power and to the armature brush.

![Figure 36: Connecting an E-Unit to a DC motor](image)

![Figure 37: Gilbert American Flyer 2 position E-Unit Disassembled](image)
The more recent engines use an electronic E-Unit driving a DC can motor. The E-Unit emulates the operation of the 4 position A.C. Gilbert E-Unit. The only difference is that if the engine is off for a certain amount of time, then the sequence will begin with the train moving in the forward direction (or in reverse if so desired -- need only reverse the wires on the motor).

### 4.4 DC Polarity

With a DC motor, simply connecting the two motor wires to the track pick-ups will work. Alternately, installing a reversing switch between the track pick-ups and the motor will control which direction the train will move for a given position of the direction switch on the transformer / rectifier.

Using DC polarity to control train direction with a universal motor can be accomplished by using a bridge rectifier to keep the polarity on the field constant. The track polarity determines the polarity of the armature (rotor) and therefore the direction of movement. See Figure 39. The only downside to this conversion is that the engine will not operate on AC track power. See Appendix A section A.2 for an alternative method that while more complex, will allow the train to travel in the forward direction on AC, and have directional control based on DC polarity.

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**Figure 38: Gilbert American Flyer 2 position E-Unit operation**

![Diagram showing the operation of a 2 position E-Unit](image)

<table>
<thead>
<tr>
<th>Position 1</th>
<th>Position 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forward</strong></td>
<td><strong>Reverse</strong></td>
</tr>
<tr>
<td>Power to Field A</td>
<td>Power to Field B</td>
</tr>
<tr>
<td>Armature to Field B</td>
<td>Armature to Field A</td>
</tr>
</tbody>
</table>

Field A
Field B

Power (Frame)
4.5 Digital Commands

Digital messages can also be used to signal an engine the desired speed and direction. This message can be communicated many ways including frequency modulation (such as DCC), radio frequency control (such as those used to control model airplanes), Infrared control (such as those used for remote control of televisions), and superimposing a signal on the track voltage (like TMCC).

Figure 40 shows how DCC used frequency modulation to send binary ones and zeroes through the track power. The complete specifications for DCC are available from the National Model Railroad Association (NMRA) through their web site (http://www.nmra.org/standards/sandrp/consist.html) The "Baseline Packet" that all DCC Command Stations and engine Digital Decoders is defined in NMRA standard S-9.2 and consists of a preamble byte (8 bits) and 3 data bytes. The three data bytes are an address data byte, instruction data byte and error detection data byte. The preamble byte is used as an indicator that data bytes will follow. The address byte contains the address of the digital decoder the message is intended; each decoder on a layout should have an unique address. The data byte contains 4 or 5 bits to indicated the ordered speed, as well as a direction bit to indicated the ordered direction. The final error detection data byte enables the decoder to determine if the first two data bytes were successfully received.
More extensive data can be communicated using extended packet formats that are defined in NMRA recommended practice RP-9.2.1.

Figure 40: Voltage waveform for Digital Command Control (DCC)\(^4\)

5. **Communicating Speed**

The following sections describe how an engine can be configured to respond to different methods of communicating speed.

5.1 **Variable Voltage (AC or DC)**

Varying the track voltage is the most common means for communicating speed. Universal and DC motors naturally increase speed when the voltage applied is increased. The precise speed however is also a function of the load placed on the motor; motors will slow down under load. The track voltage can also decrease due to voltage losses in the electrical connections between track sections. To keep train speed consistent on a floor layout, a track power connection should be provided within 4 track sections of the end of a block and spaced no more than 8 track sections apart within a block. For a permanent layout, more track power connections would be beneficial.

5.2 **Digital Commands**

Using digital commands, such as those used in DCC, can eliminate (to a degree) trains speed variation due to track voltage losses. If the decoder uses speed feedback sensors, the speed of the train can be independent of load (to a degree) as well. Since many decoders can only decrease voltage from the tracks to the motor, the track voltage limits the highest speed achievable for a given load.
6. **Action Car Considerations**

American Flyer Action cars generally fall into one of the following categories:

a. **Mechanical Activation:** No electrical power used. Examples include the Hay-jector and Tie-jector cars. These action cars are not dependent on track voltage and will not be discussed further in this document.

b. **Continuous action:** Electrical power picked up from the tracks. Examples include floodlight cars, walking brakeman cars, and action caboose.

c. **Control Button Activated.** Electrical power is provided via the "Base" rail and a pickup shoe engaging a special track section (Figure 41 and Figure 42). Examples include the TNT car, mail pickup car, log unloading car, truck unloading car, rocket launcher, operating stock car, and lumber unloading car.

![Figure 41: Special Rail Section](image1)

![Figure 42: Action car with power contact shoe](image2)
6.1 AC Track Voltage
The American Flyer electrically actuated action cars are designed to operate either on AC track voltage for those that are continuous action and on 15 volts AC for those that use the special track section and a control button. Figure 43 shows how the control button is wired to the special track section and the 15 volt accessory post on the transformer. The metal wheels on the action car must be on the rail connected to the base post of the transformer.

![Figure 43: Wiring for an Action Car with an AC transformer](image)

6.2 DC Track Voltage
Some of the electrically actuated action cars that operate off the track voltage are incompatible with DC power. One example is the Walking Brakeman car which uses a vibrating mat and requires AC power to function. Others, such as the floodlight car, and action caboose work well with DC power.

Special consideration must be made however, for action cars that use the "base rail" and the special track section. While many of the action cars will work correctly with DC power, the challenge is in providing a voltage difference of about 15 to 20 volts DC between the base rail and the special track section. The challenge is generally due to using a reversing switch to switch the polarity of the track voltage to control engine direction. If a common voltage source is used for both track power and the action car, then the voltage applied to the special track section must be adjusted when the polarity of the track power is changed. The following sections describe ways to deal with this challenge.

6.2.1 Separate Transformer
The simplest solution is to use a second AC transformer for the action cars as shown in Figure 44. The base post of this second transformer is attached to the "base rail" and the 15 volt post is connected via the control button to the special track section. Since the two transformer outputs are independent, the circuit for the track power is independent from the circuit through the special rail section, even though they share the "base rail." All action cars using the special rail section will work with this circuit.

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5 Instructions for Assembling and Operating American Flyer 3/16" Scale Trains and Equipment, Developed at the Gilbert Hall of Science, 1949.
6.2.2 Double Pole Single Throw Pushbutton

For action cars that are only used when the train is "off," a double-pole-single-throw pushbutton can be used as shown in Figure 45 provided the transformer throttle is in the "off" position when the pushbutton is pressed. The rectifier may be damaged if the pushbutton is pressed and throttle is placed in an "on" position. Although this circuit was provided by the A.C. Gilbert company, it should generally be avoided to prevent accidental damage to the rectifier.

Note that the mail pickup car should not be used with this configuration because the mail pickup car requires the train to be operating when the pushbutton is pressed.

Figure 45: Double Pole Single Throw pushbutton for controlling Action Cars with DC

6.2.3 Isolation Relay

Figure 46 illustrates how an isolation relay can be added to the circuit shown in Figure 45 to protect the rectifier from damage. Normally the relay is not energized and the normally closed contacts on the relay connect the track to the rectifier output. When the pushbutton is depressed, the relay is energized via a

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6 Instructions for Assembling and Operating American Flyer 3/16" Scale Trains and Equipment, Developed at the Gilbert Hall of Science, 1949
half wave rectifier and a 7812 12 volt regulator. A capacitor provides filtering; its value may be adjusted to adjust for different relay coil currents. The base terminal on the transformer is connected to the base track rail via the relay. The control button also provides accessory power directly to the special track section.

Note that the mail pickup car should not be used with this configuration because the mail pickup car requires the train to be operating when the pushbutton is pressed. This circuit will stop the train when the pushbutton is pressed. This circuit will work with the other action cars that do not require the train to be in motion.

![Isolation Relay Diagram]

**Figure 46: Isolation Relay**

### 6.2.4 Half Wave Rectifiers

Figure 47 demonstrates the use of a half-wave rectifier to provide DC to the track while providing AC to the special rail section. Notice that the base rail of the track is always connected to the base post of the transformer. Note that the current drawn from the transformer from a half wave rectifier is not sinusoidal and the track voltage is not a constant DC (Figure 24 and Figure 25). A filtered half wave rectifier as described in A.2 may also be used to reduce the voltage and current waveform distortion.

All action cars employing the special rail section, including the mail pickup car will work with this circuit.
Figure 47: Half Wave Rectifier with special rail section
7. **Sound Activation Considerations**

7.1 **Modulated Power**

Most AC Gilbert air chime whistles worked by superimposing a roughly 600 to 1000 Hz signal on the track power. This signal is created either with a vacuum tube in the case of the Electronic Whistle Control Box or through an electromagnetic vibrator in the case of an Air Chime Whistle Generator. Within the engine/tender, a circuit similar to Figure 48 is used to drive the speaker. Although the sound quality is usually not considered very good, this circuit works with either AC or DC track voltage. Figure 49 shows the transformer and track voltage with the Air Chime Whistle Generator activated.

If PWM is used for speed control and the switching frequency is in the audio range, then it will likely be heard continuously through the speaker. Either the switching frequency would have to be raised above the audio range, or the speaker would have to be disabled.

DCC which switches between 5 kHz and 10 kHz will probably be heard continually as well. With DCC, the air chime whistle should be disconnected.

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7.2 **DC Offset ("Railsounds")**

The 314AW engine and later engines with "Railsounds" compatible sound operate by superimposing a DC signal on AC power. The Lionel 6-5906 sound activation button (Figure 50) accomplishes this by placing in series with the track, one diode in anti-parallel with six diodes as shown in Figure 51. The push button is normally closed and thereby bypasses the diodes. When the button is depressed and opens the switch, the voltage drop across the 6 diodes in one direction is between about 3.5 and 4.0 volts DC.
and the voltage drop across the single diode in the other direction is between about 0.6 and 0.65 volts DC. The impact of depressing the sound activation button on the track voltage is shown in Figure 52. Note that the peak value in the positive direction is about 3.5 to 4.0 volts less than the peak in the negative direction. The sound board/relay in the engine/tender senses this difference to activate a whistle or bell.

Because this method of signaling relies on a difference in the peak voltage of the positive and negative half-waves, the method only works with AC track power.

![Figure 50: Lionel 6-5906 Sound Activation Button internals](image)

![Figure 51: Schematic of Sound Activation Button](image)
Digital messages can also be used to activate engine sounds. As with engine directional and speed control, this message can be communicated many ways including frequency modulation (such as DCC), radio frequency control (such as those used to control model airplanes), Infrared control (such as those used for remote control of televisions), and superimposing a signal on the track voltage (like TMCC).

Figure 52: Track Voltage when powering an unloaded universal motor and with Sound Activation Button pressed

7.3 Digital Control
8. Bibliography


This book provides detailed specifications and pictures for almost all the electro-mechanical devices in the A.C. Gilbert postwar product line. For example, if you have a burned out armature winding, this book will tell you what wire to use, how many turns, which direction to make the turns, and how to tie off the wire ends.
Appendix A: unusual technologies

A.1 Brushless DC Motors
A brushless DC motor has the permanent magnet field on the rotor, with the armature on the stator. Some type of position sensor is used to determine which of the armature coils should be energized and which polarity to use. This sensor is typically a solid state "Hall Effect" sensor that detects the magnetic field created by the field magnet. The armature coils are switched on and off using transistors. As a consequence, the commutator/brushes are eliminated. Since the life of a typical motor with brushes is limited by the brush/commutator wear, brushless DC motors can have a significantly longer service life.

A.2 Filtered Half Wave rectification for DC Directional Control
Figure 53 is a schematic of a filtered half wave rectifier for DC directional control. The advantage of this circuit over the unfiltered half wave circuit is that track voltage (Figure 54) and current (Figure 55) are much closer to a constant DC. The transformer current (Figure 56) however, still has considerable distortion. This circuit can be used with the special track section to provide ac power to action cars. One disadvantage to this circuit is that it requires two filter capacitors (unless one can find a non-polarized capacitor of sufficient capacitance). These capacitors typically have a value on the order of 10,000 uF with a voltage rating of 50 volts and can be expensive. I also recommend that the rectifiers be rated for at least 8 amps with a reverse voltage rating at least 100 Volts.

![Diagram of Filtered Half Wave Rectifier]

Figure 53: Filtered Half Wave Rectifier
Figure 54: Track Voltage: Filtered Half Wave Rectification

Figure 55: Track Current: Filtered Half Wave Rectification

Figure 56: Transformer Current: Filtered Half Wave Rectification
Appendix B: How a Commutator Works

A commutator is a mechanical rotary switch used to control current through the armature (rotor) windings on a DC or universal motor. As shown in Figure 57, The armature consists of a shaft, commutator, and armature windings around multiple poles. The goal of the commutator is to connect the proper windings on the armature to keep the magnetic fields from the field and armature as close to 90 degrees out of phase as possible to maximize the motor torque.

The wires from each of the windings can be connected in two different methods. In the Common Tie-Off method, one end of each winding are connected together and not to the commutator. The "other" end of each winding is connected to a specific commutator segment. In the End-to-End Tie-Off method, the windings are connected into a big loop; the connection between windings is also connected to a specific commutator segment.

For both tie-off methods, the commutator segments are carefully aligned with the brushes to ensure the proper windings are energized for any rotation angle of the armature. For the Common Tie-Off method, the gaps between commutator segments nearly line up with the gaps between the poles. For the End-to-End Tie-Off method, the gaps between the commutator segments line up with the center of the pole.

Most (but not all) A.C. Gilbert open frame DC and universal motors have 3 poles and use a common tie-off.

Figure 57: Armature
B.1 Common Tie-Off

Figure 59 shows how the commutator and brushes energize the rotor windings to produce a torque in the forward direction. The green and red bars on each side of the rotor symbolize the magnetic field polarity created by either the field winding or permanent magnet. In interpreting the figure, one could assume that the green bar symbolized a North magnetic pole and the red a South magnetic pole. Similarly, windings connected to the green brush result in a North magnetic pole and winding connected to the red brush result in a South magnetic pole. Figure 59 is representative of the rotor from an American Flyer steam engine. Note that the gaps between the commutator segments is rotated somewhat from the gap between the poles. This was likely done to improve forward operation without penalizing reverse operation significantly. Figure 60 shows reverse operation.

In examining Figure 59, note that at 0° rotation, winding 3 has the "green" polarity and winding 2 has the "red" polarity. Winding 1 is not energized. Since winding 3 is green and near the red pole, the magnetic force tends to rotate the rotor in the clockwise direction. Likewise, winding 2 is red and also near the red pole, hence the magnetic force is repulsive, but will still tend to rotate the rotor in the clockwise direction. At 30° rotation, the commutator has shifted supplying current from winding 3 to winding 1. This shifting of supplying current from one winding to another is called commutation. At 60° rotation, winding 1 is still green and repulsed from the green field pole and winding 2 is red and attracted to the green field pole. At 75° rotation, commutation is underway. Both winding 2 and 3 are red while winding 1 is green. Winding 3 is repulsed from the red field pole, winding 2 is attracted to the green field pole, and winding 1 is repulsed from the green field pole. At 90° rotation, commutation is complete and winding 2 is no longer energized. The situation at 120° rotation is identical to 0° with the poles all having rotated 120°.
Figure 59: Common Tie-Off Rotor  Forward Direction
B.2 End to End Tie-Off

For American Flyer motors, the end-to-end tie-off is not as common. One example is the XA15B024 armature for the 21158 Docksider (As described by Hannon 2001). Note that other Docksider armatures use the common tie-off.

Figure 61 shows how the commutator works for the end-to-end tie off method. When a winding approaches one of the field poles, the brush nearest the field pole shorts out the winding. The remaining two armature windings produce torque. When the armature rotates to the 30° position, windings 1 and 3
are in series and in anti-parallel with winding 2. Hence windings 1 and 3 are green while winding 2 is red.

DC or universal motors with more than three poles typically use the end-to-end tie-off method because except for the windings near a field pole that are being commutated, all of the other windings are energized and producing torque.

Figure 61: End-to-end Tie Off Rotor Rotation
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