VOLT METERS VS AMP METERS - Fitting a Volt meter to a Triumph TR4A and keeping the Amp meter.

Dr. Hugo Holden, Dec 2011.

Background:

In general it was standard practice to fit ammeters (Amp Meters) to cars where the battery charging system was dynamo based. When alternators began to be fitted to cars in the 1960's, amp meters were for the most part discarded and replaced by volt meters. These two types of meters measure fundamentally different things. The amp meter is a rate meter and the volt meter is a potential energy meter (this is explained below). Neither type of meter measures the battery's state of charge or residual energy capacity. Newer types of microprocessor based meters calculate (estimate) the residual capacity based on the battery's voltage level and how it has been changing with time. These are sometimes called battery "fuel" meters and are popular in golf carts. A range of these meters is made by Curtis Instruments in the USA.

For those not greatly familiar with electricity or electronics, one way to make this subject easier to understand is to make the electrical values of voltage and current analogous to those of pressure and flow of water. Everyone knows you can still have a pressure in a pipe with no flow at all, as is the case when the tap is turned off. However you can't have flow without any pressure. The same applies to electrical voltage and current flow.

The reason why pressure is analogous to voltage is not very obvious because we are nearly always presented with pressure values in force per unit area, eg Pounds per square inch or Newtons per square meter in the metric system. Sometimes we are presented with pressure numbers relating to a column of fluid with gravity acting on it. This is because the product of gravity, height and fluid density is a pressure. The units we then use are say centimetres of water millimetres of mercury for example, which is a length. So what are the units of pressure which give more insight into what is really happening?

To understand what pressure really is we need to put it in better units. If we start with Newtons per square meter or N/m^2 and multiply both Newtons and square meters by meters, so that the ratio is unchanged, then the units are Newton. meters per cubic meter or $N.m/m^3$. The product of force and distance, or Newton.meters, is *work*, which has the units of Energy or Joules J.

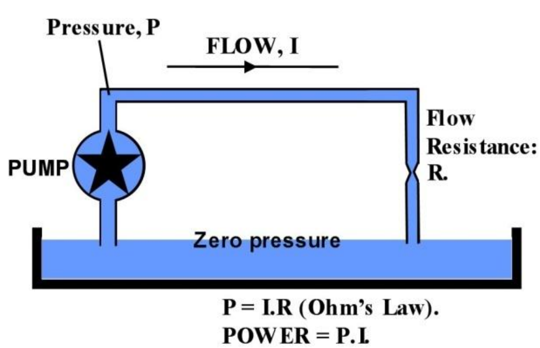
Cubic meters or m^3 is a *volume*. So now we discover that a pressure has units of Joules per cubic meter, or J/m^3, which is an “energy density”. (The usual “density” most people are familiar with is “mass density” which is mass per unit volume). So in reality “pressure” is an energy density and therefore a potential energy source. For example; one cubic meter of fluid acted on and passing through a pressure gradient of say “Ten Joules per cubic meter” would acquire 10 Joules of energy from that pressure source. Or put another way, to push a cubic meter of fluid across and against a 10 J/m^3 pressure gradient would require 10 Joules of energy.

Fluid flowing past a point in the pipe can be measured as the volume flow per unit time or cubic meters per second for example.

In the electrical example Voltage like a pressure is an energy density and has units of Joules per Coulomb of electrical charge. A Coulomb (Co) is merely a large volume or number of electrons, 6 x 10^{18} of them, just as a cubic meter is a large volume of fluid. When one Coulomb of electrical charge passes by two points in a circuit and a voltage difference of 10 volts between these points, then the energy given to the charge of one Coulomb is 10 Joules. Likewise to force a single Coulomb of charge across and against a 10V voltage gradient would require 10 Joules of energy.

Electrical current flowing by a point in a circuit can be measured as Coulombs per second of electrical charge. Like cubic meters per second in the fluidic system, this is a flow rate.

Initially if you compare the two diagrams below relating to the flow of water and the flow of electrical current they are very similar:



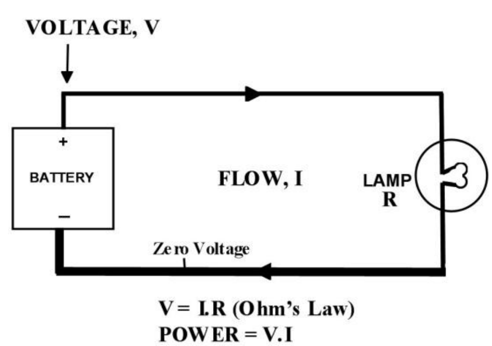


FIGURE 1. FIGURE 2.

The pump in figure 1 picks up fluid from a zero pressure potential and raises the pressure to a value P, lets say 10 N/m^2, or better put 10 J/m^3 since the pressure is an energy density. Let us assume that the pipes carrying the fluid have a very low flow resistance and most of the flow resistance R, is in the narrow constriction. Here the energy that was given to the fluid by the pressure source is dissipated as heat and sometimes noise (turbulence). The fluid travels around in this example in a circuit because it is returned to the surface of the same container. In reality it could be two different containers in two different places for this fluid example, but still the fluid is returned to the zero pressure reference value (which in general is atmospheric pressure in practice). For every cubic meter of fluid acted on (that passes via the 10 J/m^3 pressure source) then 10 J of energy is given to that cubic meter of fluid.

In the electrical example the battery generates a voltage (or electrical pressure) and this results in a current of electrons (rather than water) around a circuit. Again we assume that the resistance to flow in the wiring is very low and that most of the resistance is in the lamp or load where the energy given by the voltage source to the electron flow is dissipated by the lamp as heat and light. If we say the voltage is 10V, then every Coulomb (Co) of electrical charge (electrons) acted on by the voltage source is given 10 J of energy.

In the electrical example and all electrical circuits there are a few extra things to note. The electrons always travel around a circuit back to where they came from. If they cannot then an electrical charge, plus and minus, builds up on each side of the discontinuity (broken circuit) and ultimately the current flow stops as the charge builds up sufficiently to repel the flow of electrons. (A good example of this is the charging of the plates of a capacitor when the capacitor is connected across a battery, current flows for a while only while the capacitor is charging but ultimately stops as the plates charge up repelling further flow).

Also to confuse the uninitiated, the flow of "conventional current" as shown in the diagram of figure 2, from the battery's positive terminal to its negative terminal is in the opposite direction to the actual flow of electrons. As one might guess electrons being negatively charged are not likely to flow away from the positive terminal toward the negative terminal. The only way to force them toward the negative terminal is with another voltage supply higher than that of the battery. This of course is the process that is required to charge the battery from a power supply with a higher voltage than the battery, like a battery charger or dynamo or alternator.

Other features of electrical current:

The flow of electrical current or electrical charge, with respect to an observer, creates a magnetic field around the conductor or stream of electrons. The magnetic field associated with an electrical current is the basis of all electromagnetic machinery, including generators, electric motors, solenoids, moving coil and moving iron meters, radio transmitters and every electrical or electronic device that exploits the principles of electromagnetism or contains any sort of inductor or inductance.

The magnetic field of a current flow vanishes if the observer has the same relative motion as the current. This is an interesting relativistic finding and represents one of the most important observations made about the physical nature of Electromagnetism and our Universe.

In both examples above, hydraulic or electric, neglecting wiring resistance energy losses or fluid friction in the pipes, the power being dissipated by the resistances R of the lamp or the constriction in the pipe, is simply the product of voltage (or pressure) and flow. Juggling Ohms law and the power law around algebraically it is easy to see that the power is also equal to $I^2.R$. This is in fact the best way to consider what flow resistance is and what it does. Resistors waste or “dissipate” power directly proportionally to the value of the resistance and proportionally to the square of the flow.

As an interesting aside - some notes on “resistance”:

Substances which conduct electricity, generally metals, have an abundance of free electrons which are mobile enough to move under an applied electric pressure or voltage. In a metallic conductor the nuclei of the metal atoms, which are in a lattice like configuration, bathe in a large sea or “gas” of electrons. When an electric field or voltage is applied the electrons drift under the force of the field and would keep speeding up (accelerating) if they were not retarded by a force of friction which ultimately balances the applied electric force. Electrical resistance arises from interactions of the electrons with the vibrating nuclei of the crystal lattice and to some extent with any impurity atoms present that distort the architecture of the lattice.

When no voltage is applied to an electrical resistance and no electron drift current is flowing through a metallic conductor, there is still random motion of the electrons due to their temperature, a type of Brownian motion. Given that any current passing through a resistor will generate a voltage across the resistors terminals, then this random motion produces a *noise* voltage across the resistor’s terminals. This noise sets a limit when amplifying very weak or small amplitude signals, like those that Radio-Astronomers want to detect from deep space. This type of noise is called Johnson noise and its rms (root mean square value) value is proportional to the square root of the value of the resistor R and the square root of the absolute temperature (Kelvin scale) T and the square root of Boltzman’s constant k. B is the noise bandwidth in Hz. The formula being:

$$\mathrm{Vrms} = (4kTRB)^{1/2}$$

For example a 10k resistor just sitting there at room temperature has a voltage of 1.3 micro-volts over a bandwidth of 10KHz across its terminals just due to the random thermal fluctuations of electrons in the resistor. While this does not relate greatly to automotive electronics, it is still none the less very interesting.

In the case of resistance with fluid flow the same applies in that under the influence of a pressure the fluid would keep accelerating if it were not for some retarding force of friction. This friction or resistance is caused, in the case of laminar flow, by layers of fluid sliding upon each other and friction between those layers and the fluid's viscosity is important in determining the value. The resistance here increases inversely with the 4^{th} power of the tube's or pipe's radius. So for example halving the pipe diameter increases the flow resistance by 2^4 or 16 times. If the flow becomes turbulent the particles that can be imagined to comprise the fluid have chaotic motion and exchange energy and momentum with each other and energy is lost in those collisions. This happens in narrow constrictions in pipes. In this instance the viscosity is not important and the fluid's density is important in determining the resistance. This type of flow resistance is also dependent on the flow rate and the roughness of the pipe wall becomes important too.

In all cases as noted, *resistors* can be regarded as being objects which do two basic things:

1) Dissipate (waste) energy as heat according to the formula: $I^2.R$

2) Convert a current passing through them to a voltage across their terminals: V = I.R

To summarise:

Hydraulic pressure and electrical voltage are both potential energy sources. In the former case energy is imparted to a volume of fluid that passes by points of different pressure (higher to lower). In the electrical system energy is imparted to the volume of electrons passing by points of different voltage. In both systems there is a flow rate. In the hydraulic system it is volume of fluid per second or m^3/s, and in the electrical system it is Coulombs (Co) of charge per second or Co/s, known as **Amps.**

With the flow of fluid or electron flow there is energy loss due to friction and the energy imparted to the fluid, or electrons, is dissipated as heat. Devices or mechanisms that preferentially dissipate heat with flow are called *resistors* or resistances. One interesting point to note is that the resistance values of resistors in electrical systems are generally fairly independent of the flow rate or current and are often influenced by temperature. For example a lamp filament has a much lower resistance when it is cold than compared to when the lamp is running. The resistance of a copper conductor increases a little with temperature. Semiconductors tend to do the reverse and have a negative temperature coefficient.

The units of resistance therefore are units of pressure divided by flow. This is the famous **Ohms Law** relation that Pressure = flow x resistance generally stated as V= I.R for electrical circuits.

A couple of simple examples for the hydraulic or electrical system:

A 10 Joule/cubic meter pressure source drives fluid through a flow circuit with a total flow resistance, R of 10 J.s /m^6 What is the flow rate ?

P/R = I, therefore the flow rate is 10/10 = 1 cubic meter per second or 1m^3/s.

OR:

A 10 Volt power supply drives a current through a 10 Ohm resistor, what is the flow rate or current?

V/R = I, therefore the current is 10/10 = 1 Coulombs per second, 1 Co/s, or 1 AMP.

Notice the term “Ohm”, when you look at the units is Volts/Amp or Joule.seconds / $Coulomb^2$

It is much more of a mouthful to say Joule seconds per square Coulomb than “Ohms”.

Of note is that in each case, hydraulic or electric circuit, the power dissipated by the flow resistance is the product of Voltage and current, or pressure and flow rate:

Power = P.I =10 J/m^3 x 1m^3/s = 10 J/s = 10 watts for the fluidic system.

Power = V.I = 10 J/Co x 1Co/s = 10 J/s = 10 watts for the electrical system.

So with the above explanation it is easy to see that the volt meter is a potential energy meter. You can therefore think of voltage as an “electric force field” which places a physical force on an electric charge in proportion to the voltage value. Therefore the battery voltage is able to do physical work on the charge. Also to move the charge against the voltage field an external energy source of a higher voltage, like a battery charger is required. Hydraulic pressure places a physical force on a mass of fluid. In each instance a “Transport Phenomenon” occurs in that electrical charge, or fluid in the hydraulic case, is moved from one location to another and the amp meter (or a water flow rate meter) observes the electrons or fluid passing by some point in the system.

In general terminology voltage is measured *across* part of a circuit, often with respect to negative or earth as it is sometimes called. Current flows *through* circuit elements, wires and components etc. So it is always incorrect to say something has a voltage passing through it.

Also any object or device in series with another in a circuit must have the same current as any other component it is in series with.

How voltage and current meters work:

In general it is obvious that a current or amp meter would be placed in series with a circuit and a volt meter in parallel with it.

In the case of volt meters one method is that the volt meter draws a small electrical current via a coil (moving coil meter)**.** The magnetic field generated by the current in the wire coil interacts with a fixed magnet and deflects a needle attached to the coil as the coil rotates. A moving iron meter is similar except the coil is fixed and two vanes of iron are magnetised. One is fixed and the other moving. The vane attached to the needle repels the fixed one. Hot wire gauges are popular in cars, such as the standard Smiths volt meters because they are heavily damped and there is minimal needle flutter. These draw current and heat a heater coil or heater element. This acts on a bimetallic strip to deflect the needle. Modern electronic volt meters measure the voltage using an electronic amplifier and Analog to Digital conversion to drive digital display. Yet another type uses a stepper motor to control the needle position. These give a very accurate and stable display in a car. It is interesting that nearly all volt meters draw a small current, except for those which use insulated gate field effect transistor as the input device, or a vacuum tube, and even these include a high value parallel resistance perhaps 10 million Ohms to discharge the gate or the grid circuit.

In general volt meters may be inaccurate if they draw a lot of current with respect to the resistances of the circuits they get connected to. They load the voltage down at the point of measurement giving a falsely low reading. Most modern digital meters draw very little current from the circuit they are connected to, so give very accurate readings. Digital display meters are however not wonderful in cars on instruments where the data is varying. As the display changes value it takes longer for the human mind to decide what the average value is. Damped Analog meters are far better at a glance. After all you should be looking at the road most of the time.

Amp meters can be constructed in a number of ways. Moving iron types or variations of these are common. Some current meters detect the magnetic field with a Hall Effect Device, which is a type of magnetic sensor which is usually configured with an IC to provide a voltage output that is proportional to the magnetic field of the current. The simplest way to detect and measure a current is to convert the current into a voltage by passing the current through a simple resistor and then using a volt meter to measure the voltage drop across the known resistance value, which from Ohm’s law is I.R. The only problem with this is that the resistors wastes energy as heat equal to $I^2.R$, so this method is not great for high currents as the voltage drop gets too high or the power loss is too high.

The Battery and its I.R drop:

Batteries are rated for their Voltage and Ampere-Hour capacity. For example with a fully charged 20 ampere-hour rated battery you could expect to be able to get 20 amps from it for 1 hour, or for example 1 amp for 20 hours very approximately. If you were charging it up with a 1 amp current then this would be expected to take 20 hours approximately.

The *total energy* stored in a fully charged 12V 20Ah battery, assuming the battery could maintain its voltage to around 12V over its full discharge is easily calculated. For example if the load current was 1 amp and the battery voltage 12V then the power delivery is 12 watts or 12 Joules/second. The battery capacity is 20AH, so it can deliver the 1 amp for 20 hrs, so the total energy is 12 x 1 x 20 x 3600seconds = 864,000 Joules or 864kJ.

Car batteries have a number of interesting physical properties beyond the scope of this article. For example their internal resistance increases with decreasing temperature. When they are fully charged, rather than storing more energy with changes to their internal chemical structure, they generate heat and gas instead and the charging energy is wasted.

Although a car battery has two big solid terminals, you can't actually connect directly to the voltage source that comprises the electrochemical and charge storage system that is the battery. The battery behaves as though it is a voltage sourced through a small series resistance. This is called the *internal resistance of the battery* and it acts like a resistor in series with the battery. In general it is in the order of 10 to 60 milli-Ohms for a car battery and gets much higher with a sick or sulphated battery. As noted above whenever charge or current flows via a resistance then a voltage of magnitude I.R is dropped across the resistance. This is why the voltage, measured directly across a battery's terminals drops down as current is taken from the battery and increases when current is delivered to the battery for example during charging.

The I.R drop from the battery's internal resistance is *one* of the reasons why a volt meter in a car has utility value. The internal resistance means that the battery terminal voltage will climb up with the battery charging and fall down with the battery discharging. Obviously, if the battery terminal voltage was always a constant, the volt meter would be a fairly useless instrument.

Also the state of charge of the battery is proportional to its terminal voltage. This means that there are two types of information that can be gained from the volt meter:

1) The battery's state of charge seen when the battery is off charge, ignition on and engine not running.

2) Whether or not the battery is likely to be charging or discharging while driving can be deduced from the terminal voltage, the magic number is 13V as explained below.

Amp Meters vs Volt meters in the car.

The Amp Meter:

The amp meter in the car is connected in series with the battery and the charging system. All of the electrical loads in the car like a TR4A (except for the starter motor and horns) are monitored by the amp meter. The amp meter measures current going to and from the battery. For example with the charging system not operating (dynamo or alternator off) switching on the lights results in a negative deflection of the amp meter needle. On starting and running the engine the charging system then supplies the current to the lamps and also to the battery, so the lights brighten a little and the amp meter displays a positive deflection. It should be noted that the *total* current, supplied by the charging system is the difference between the positive and negative deflection because the positive deflection is charge current and the negative deflection was the load (headlight) current and the charging system is now supplying both of these.

So with the amp meter the driver can see if the battery is being charged or discharged but is left to guess how much energy might be available at some discharge rate, eg how long it will take for the battery to fully discharge, or how long it might take to get the battery to full charge. However there is a clue to the latter. A battery's charge current drops off significantly as it approaches full charge. This is especially so in constant voltage charging systems where the voltage is stable at around 14.2V. A discharged battery could draw 20 amps from that charging system and only about one to a few amps when fully charged, and this can be seen while observing the amp meter.

Therefore the A**mp meter** gives the following information:

1) The battery's charge or discharge current at any point in time.

2) The total load on the charging system can be determined as the difference between the discharge current and the charge current as noted above.

3) A low charge current after a long period of higher charge current indicates that the battery is probably fully charged.

4) One expects to see a higher charge current after an extended period of discharge current.

5) No charge current suggests charging system failure, the ignition light comes on. It could be a broken fan belt, if so the engine temperature increases rapidly as he water pump also has stopped. If this does not happen and barring any faulty connections or wiring, the dynamo or alternator and or its voltage regulator has probably failed if the charge current vanishes.

The Volt Meter:

If a volt meter is connected directly across the battery's terminals, the voltage recorded gives an indication or a clue of the state of charge of the battery. If the battery has been sitting a while and not freshly charged, a voltage of 12.6v to 13v is consistent with a well charged battery and 12V is a reasonable value. A voltage under 11v would suggest the battery is probably in a discharged state. If a battery has just been on heavy charging the voltage off load could read as high as 13.8 volts for a while.

In many cases the actual volt meter in the car is not connected directly onto the battery terminals, but on to a connection in the ignition circuit so that the meter which consumes a small amount of energy, is not running unless the engine is on. Any current I, flowing in this ignition wiring, with a resistance R, will cause a I.R type voltage drop across the wiring. This means that the voltage measured can be a little lower than the battery's actual terminal voltage. For example if a volt meter is connected to the wiring that supplies the heater blow motor (a bad choice of connection location) then the voltage reading will drop when the blower is turned on, a lot more than it would if the meter were connected across the battery directly as the battery's internal resistance is very low compared to the wiring resistances.

Due to the internal resistance inside the battery the volt meter reading will drop when current is taken from the battery and increase when current is transferred to the battery during charging. In general most volt gauge manufacturers concluded that if the applied voltage, from a charging system, on the batteries terminals, was 13.0V and that if the battery was full charged, then the battery's charge current would likely be very low to zero. If the voltage is greater than 13.0V then likely the battery is "on charge" and if lower than 13.0V the battery is likely discharging. Therefore many Smiths car volt meters are labelled this way. The 13.0V figure is regarded as the "charge neutral" voltage.

Therefore the **volt meter** in the car gives the following information:

1) With the ignition on (motor not running) the battery voltage is a good guide to the state of charge of the battery. 12V to 13V suggests a satisfactorily charged battery, and 11V or less suggests it is discharged and <10V very discharged. This feature is the reason why volt meters are sometimes loosely referred to as battery condition meters.

2) With the engine running, a value of 13V suggests no net charge or discharge, greater than 13V the battery is on charge and less than that probably on discharge.

3) The voltage should not go above 15V or it is likely the battery is being too aggressively charged. The voltage set point for most alternator systems is around 14.2V.

4) With the car in use & battery constantly under 13V, and the ignition light on, the charging system has stopped working.

One dilemma with automotive voltage meters is their faces are often not well calibrated and they can have been connected into parts of the cars wiring where there are voltage drops caused by loading from accessories and wiring resistance of a value much higher than the internal resistance of the battery itself. One way to assess this is to look at the volt meter reading on its face and measure the battery terminal voltage with a known good digital meter. Then a correction value/factor will be known.

In summary:

Volt meters and Amp meters provide different information. Overall the amp meter when understood provides the most information for a single gauge. Even the battery's suggested state of charge can be guessed at via the battery's charge current. However the volt meter gives a good indication and really, in the ideal world, a car would be fitted with both meters. That is for those of us who are interested in the workings of their car and wanting a technical interface with their machine. We all know how manufacturers have concluded that the only indicator most people would want is a "check engine" light and when that gets annoying they would expect that you would put a sticker over it to hide it.

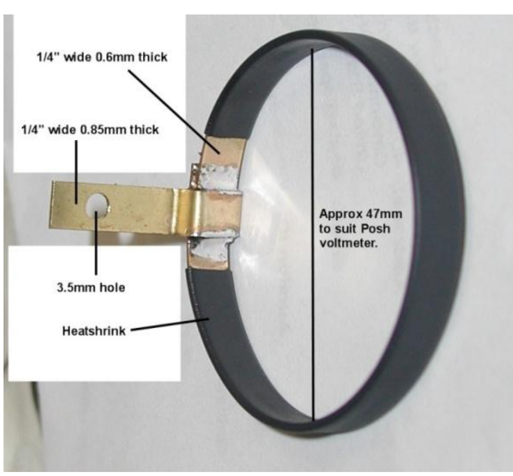
Fitting a voltmeter to my car is useful in evaluating various electronic RB106 substitutes.

Fitting a volt meter to a TR4A & keeping the Amp meter:

One problem adding extra or non standard instruments to a car is where to locate them. Especially so they don't occlude the view of other instruments. Also one wonders if it is worth drilling a large 45 to 52 mm diameter hole somewhere to add a gauge. Or perhaps mount it on a bracket on the lower dash edge. On inspecting this situation on a TR4A, one thought was to put a volt meter in the ashtray area and dispense with the ash tray. After some deliberation I concluded the best place to mount it was directly on top of the steering column. The photos show how this was done. The type of volt meter chosen is a Motorcycle accessory which is fully encased and about 47mm in diameter. A little smaller than the usual 52mm diameter Smiths instrument. It has a ¼ diameter black cable exiting its rear and contains 3 wires. The black is for ground, the red +12V and the green is for the internal lamp it contains which is an LED.

The meter came from a Japanese supplier via the Web!ke website and is made by POSH - FAITH Co Ltd. Japan. The needle has excellent damping, I think critically damped or just over that. The needle makes a swift movement to its angle with no overshoot or oscillation. It is possibly a moving iron type, I have not opened it as it is a weather proof sealed unit. The face is well calibrated over the 8 to 16 V range and the illumination is even and very pleasant looking. The case appears to be either plated brass or stainless steel. The unit has a glass face.

A bracket was fashioned and soldered together from some K&S brass strip as sown in the photo below:



The brass strip, with the 3.5mm hole, slips under the cowling and the original cowling screw fixed this bracket. The cable exiting the rear of the meter is cable tied to the steering column which gives some additional support. Mounted in this position the meter does not obstruct the view of any other instrument. The idea is that it is easy to remove to return the car to original. The black wire is grounded with a lug under a nut on an existing bolt under the dash. The red wire is connected to the white wire on the overdrive relay (which is connected to the ignition circuit) the green wire is connected to the red/green wire that originates from the light switch. It could also connect to the rheostat that controls the other instrument lamps. I tend to have these on full always with night driving. The photos below show the unit in the car:

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