It’s not a switch: A new way to actuate door locks

David Swanson - February 19, 2017

It was 1914 when the Scripps-Booth car company first introduced electrically controlled door locks. I am not quite sure why anyone would put door locks on a vehicle that appears to have no windows. I am thinking others thought the same. This feature was fairly short lived. It wasn’t until the 1956 Packard came along before electric door locks were tried again. And that was when they started taking hold (thanks Wikipedia). Cars had windows then ;-) My point is that electrically controlled door locks have been around for quite some time. The technology they incorporated back then was somewhat lacking when compared with the automotive requirements of today... AECQ100, fault mitigation, safety integrity level, FMEA.

For example, fault mitigation (i.e. protection) was best defined as survivability. If nothing caught fire, we were good. So what protection there was came in the form of a fuse, either in the power distribution (fuse) box or (later) in the form of a resettable fuse in the motor. There were no diagnostics. The locks worked, or they didn’t.

Over 100 years after the Scripps-Booth introduction, almost all door locks in North American cars are electrically actuated. They use a simple H-Bridge circuit either in the door zone module or in the central Body Control Module (BCM). In reality, it’s just a few switches. Battery on one side and ground on the other. Mostly, door lock actuators are driven by relays. Their protection has changed little since 1914 (If nothing caught fire, we were good).

For most North American cars, typically one side of the driver’s door lock is driven separately from the rest. That translates to a configuration using three single pole, double throw relays. So very simple. There are more complex solutions out there, but the vast majority fit this simplest of descriptions.
Relay specifications for door lock actuators center around the needs of relay selection. Specifically, peak current and the number of actuations required before failure. This tended to make the specified currents higher than needed (for margin). Relays are the sledgehammer of switches. Whack and it works. If it doesn’t, then, oh well. That’s what fuses are for. And relays are slow, noisy, bulky, heavy, and have a relatively finite number of actuations before failing. As a result, they tend to be unreliable when compared to semiconductors... It makes sense that we would evolve into something a little more sophisticated than a 1914 sledgehammer. Something faster, quieter, smaller, lighter, more flexible and very reliable... solid state.

When considering a solid state solution based on these same parameters, semiconductors can beat
the spec for number of cycles or actuations in their sleep. For a power MOSFET, 100k cycles can be done in the time it takes to blink. Comparatively, a relay might have a bit of trouble getting to 100k cycles in its lifetime.

MOSFETs can easily have a lower on resistance than a relay as well. This whole thing is very doable in solid state. Having that low of an on resistance makes for a costlier solution than what is necessary, at least more expensive than a comparable relay. In automotive body electronics, car makers think that features are great as long as they are free. So now, to save us money, we want to consider other things not thought about before. So we consider things like switch power dissipation, transient thermal impedance (junction temperature over time), or overcurrent protection. With all that considered, the solid state solution gets less expensive. But wait! There’s more!

**Added value**

Solid state solutions provide more flexibility in configuration, can unlock the door much faster for smoother passive entry access, eliminate the annoying sound of the relay. By controlling the lock motor current, solid state can soften the sound of the door lock itself, as well as reduce the wear and tear on the door lock assembly. The added flexibility can allow for remote unlocking of specific doors for limited or secure access or individual passive entry actuation.

Electronic solutions can confirm that a lock was actuated properly. This feature can be used to improve passenger safety and security should functional safety standards for door locks become an issue. For the car manufacturer, the integrity of the lock circuitry can be confirmed electronically for assembly line diagnostics. Momentary shorts don’t blow a fuse and disable the entire system. On the contrary, the fault can be quickly diagnosed and isolated, thus reducing warranty costs.

All, or at least most, of this can be realized using relays, but it takes a considerable amount of external components to do so: Sense resistors, voltage detectors, bias circuits, latching mechanisms, for example. All of which can be integrated into a single chip. So, sign me up. How can we do this without mortgaging the house?

**Motor behavior**

There are some concepts we can take advantage of to reduce the cost of a semiconductor door lock driver solution even more. The first is to move our focus from the maximum current the door lock motor can demand (what a relay spec would require) and focus on the minimum motor current required to actuate a door lock in any condition. Allow me to explain.
Peak current for a door lock motor occurs when the motor is stalled. Oddly, once the motor is stalled the lock is finished with its task. Yet stall is where the motor sits for a large percentage of the cycle.

Stall current is both voltage and temperature dependent. Typically, in an automobile, temperature and voltage are inversely proportional. In a normally functioning charging system, when the vehicle temperature decreases, the alternator regulates at a higher voltage to take advantage of the battery’s ability to take a charge.

![Figure 2](Image)

**Figure 2** Typical voltage over temperature curve for a standard alternator regulator

Also, it is noted that as a standard copper wound, brush type motor temperature decreases, the motor stall current increases. As a result, there are two extremes the door lock mechanism must operate under. The first extreme is at the lowest temperature where the battery voltage is the highest and the motor winding resistance is the lowest. This is where the relay specifications take their cue. The second extreme is at the hottest temperature where the battery voltage is the lowest and the motor winding resistance is the highest. Both have their challenges.
Another interesting thing about motors is that motor torque is directly proportional to motor current. Higher current means higher torque. So at cold temperatures and high voltages, there is much higher torque imposed on the door lock mechanism than at high temperatures and low voltages.
The door lock mechanism must work at both extremes. This means the motor current seen at high temperatures and low voltages must be sufficient to drive a door lock mechanism at any temperature or voltage – with some margin. The colder motor might be a bit more resistant to moving and may take a tad more torque to move. It sure doesn’t need the massive amount of torque produced from the current delivered by a 16V+ battery at -40°C.

When I talk to door lock actuator manufacturers, they are much more concerned with high temperature and low voltage. That is the challenge when using a relay to drive the motor. At higher temperature the lock mechanism may move easier, mechanically, while having a harder time to actuate due to the lower the current created by the lower voltage and higher winding resistance. The lower current generates a lower torque with which to move the mechanism.

The relationship between motor current and torque are described by the following equation:

\[ T = \frac{PN}{2\pi} \phi \]

Where:
- \( T \) is the motor torque
- \( N \) is the number of coil turns
- \( P \) is the number of poles
- \( \phi \) is the flux
- \( I \) is the current in the motor

Note that all of the parameters are virtually fixed. \( N, P, \phi \) are motor parameters that are governed by the construction of the motor itself. That means that we can simplify the equation to:

\[ T = k \times I \]

Where \( k \) is a constant. The conclusion can be made that regardless of temperature or voltage or motor speed, the torque in the motor is governed by the current in the motor.
Run currents, on the other hand, tend to stay the same over temperature, only changing to accommodate an added mechanical resistance due to the effects of cold on the grease.

Relay solutions cannot regulate the current, and therefore must be able to sustain that worst case high current operation. Semiconductor solutions can regulate their current and therefore can function at the lower current end of the spectrum and still safely do their job.

**What about stick-tion?**

The last characteristic of a lock motor we want to consider is the current seen when the motor is first started up: stall current. Stall current is important ... well, not really that important. Door lock motors start up just fine even when their current is regulated to the stall current seen at the lowest voltage and highest temperatures. At very low voltages, there can be little appreciable difference between start-up and run currents. As a result, the current in the motor during start-up or stall can be limited to that of normal run current with very little effect on actuation timing.
The semiconductor solution for door lock actuation can take advantage of the fact that a door lock motor is designed to actuate at 85°C and something less than 9V. Setting a fixed current in a motor will generate the same amount of torque out of the motor regardless of battery voltage or motor temperature. Therefore, limiting the current in the door lock actuator to that of a 9V system at 85°C may very well be sufficient to actuate the mechanism successfully at any temperature or voltage.

**Figure 5:** Typical GM door lock current at low voltage and 85°C

**Figure 6** Run vs. stall current at 85°C
In doing this, we drive the lock motors at a fraction of the original current requirements. Power in the switch is proportional to the square of the current. So a reduction in current by 50% is a 4x decrease in power in the switch. That power reduction can be taken up by increasing the resistance ($R_{DS(on)}$) of the switch, thereby making the overall solution much more cost effective.

Other benefits include a cooler lock motor that can withstand a lot more abuse before overheating. In some cases, the current can be regulated such that there is no overheating, even after an hour of lock-unlock actuations.

The solution

To provide a system where one side of the lock motors is served by a simple half bridge and the other side is served by current regulated half bridges. For the simple North American three relay circuit, it would look something like Figure 7.

![Figure 7](image)
Here one current regulated output drives the driver’s door lock, and the other current regulated output drives the other three lock motors in parallel. The first thing this schematic brings our attention to is the paralleled motors. What happens if one or two motors are already in stall when actuated?

How well can motors share current?

Let’s examine the case where one lock motor unlocked and the other two locked. The node that shares four motors is unregulated (just a switch). A lock function will see two stalled motors and one (hopefully) running motor. The concern is that, in a heavily current regulated system with three motors in parallel, the two stalled motors will hog all of the current keeping the unlocked motor from moving.

When the system is first actuated, until the unlocked motor begins to move, all three motors are in stall. As a result, the current is shared quite nicely, providing enough torque for the unlocked motor to move. It is only after the motor begins to move that the other two stalled motors can siphon off its current. The “siphoning” of the regulated current by the stalled motors is proportional to the speed of the moving motor. Consequently, the unlocked motor moves a tad slower. But still well within the timing requirements.

Figure 8 illustrates the currents shared by (in this case) four motors where only one is not in stall. The magenta shows the total current of the three stalled motors, and the green shows the current in the un-stalled motor. Even with this worst case study, the motor still moves.
Figure 8 Sharing currents in parallel motors

This example shows a heavily regulated 4A total current system. The stall current each motor wants to see is ~2A each. We are regulating to half of that in this example. The four motors are then sharing the limited current between them. Three stalled motors can easily take all of the regulated current if the fourth motor was not present. In the end, the run time for the un-stalled motor to fully actuate in this heavily regulated system is still less than half of the system specification.

Not all door lock systems are the same

Many door lock systems are not so simple as that shown in Figure 1. Many have secondary locks and some have a third lock motor in each door. I have seen lock strategies with up to 10 motors. Considering that there are several ways that the locks can be driven: Driver’s only, rear doors only, hatch only, front passenger only, child locks vs. Thatcham requirements for just a few examples. The myriad of configurations is confusing. Relays were good because they could drive any of them without concern for currents. However, many solutions make for many relays. In some of the configurations, because relays can only be high or low with no “off” state, there can be multiple actuations for a single function.

The universal solution
Wouldn’t it be great if there was an IC able to control all door lock configurations using a minimum of external components? A system that could reduce the peak stall current requirements to something within reason and still safely actuate lock motors? Lock motor current can easily be regulated by a simple PWM current regulation. This reduction in current by means of PWM control reduces the power requirements in:

- The wiring
- The circuit board
- The silicon
- And it reduces mechanical stress

Once we go to a solid state solution, we can take advantage of the features solid state provides fairly easily. Things like:

- Open load detection (on and off state)
- Shorted output detection and protection (on and off state)
- Die temperature feedback for abuse mitigation
- Silent operation!

Well, there is an IC in the works, the L99UDL01 Universal Door Lock driver.
Figure 9 illustrates the potential to drive 8 lock motors in a footprint less than a quarter the circuit board area it would take if done by relays and a relay driver. The weight saving by components alone is better than 10:1. The reduction in copper area needed to carry the lock motor current is significant as well.

This device has 6 current regulated outputs able to regulate current from 1A to 4A each. There are two external half bridge controllers that drive and protect external MOSFETs. The above configuration only takes advantage of one of the external half bridge controllers. The other can be configured as a protected half bridge, a protected high or low side driver.
The L99UDL01 Universal Door Lock IC is fully programmable, requiring very little microcontroller resources to actuate. By sending a few SPI commands the microcontroller can set up and actuate the locks with timed actuation and dynamic braking. Through SPI the micro can ask for and receive diagnostics for on and off state load integrity checks. There is an emergency mode that provides for severe load driving in the face of a compromised wiring harness. This emergency mode is arguably more capable than a relay and a fuse when in adverse conditions.

The programmable feature set includes:

- Actuation duration (how long the locks are driven)
  - From 100ms to over 1s
- Dynamic braking duration
  - From nothing to DC
- Current regulation
  - Amplitude
  - Frequency
- Paralleling outputs for higher current capability

This concept in door lock actuation is a complete paradigm shift from the past 100 years of electrically controlled locks. The focus moves from the worst case high current for a cold motor at stall and high voltage to the minimum drive current actually needed for safe and reliable motor actuation. The focus moves from brute force protection using a fuse—disabling the entire system—to what is considered reasonable protection of body control module outputs today.

Virtually all of the body control module outputs today are individually protected against shorts to battery or to ground as well as sensed for open load conditions. These drivers provide overcurrent protection as well as thermal protection. In other words, they are intelligently driven. Door lock drivers should list these features as well. Intelligent locking.

It’s not just a switch.

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- Keyless Car Access: More Options for Drivers
- Hack a hotel lock with a dry erase marker and Arduino