Robustness to unintended ignition key rotation with key ring only

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Robustness to unintended rotation with key ring only

- Physics
  - Symmetry about neutral axis with little unbalanced mass results in negligible input moment to cause rotation (see Figure 1A)
- Physical Tests
  - 4 Vehicles tested (Chevy Cobalt, Saturn Ion, Chevy HHR, Pontiac Solstice)
  - Conducted over 100 full vehicle tests with nothing attached to the key, or with an empty key ring involving extreme maneuvers on severe road surfaces as well as on full vehicle simulator.
  - <u>Test results show no instances of unintended key rotation.</u>
    - Aggressive Road tests:
      - Ride and Handling loop @ posted speeds
      - Belgian Blocks durability schedule
      - Pothole #1 strikes
      - Pothole #2 strikes
      - Cubilete @ 10 – 15 MPH
      - Panic stop from 10 – 15 MPH
      - R&H Chatter @ 45 – 55 MPH
      - R&H Angled RR crossing @ 70 – 80 mph
      - Median crossing from 15 – 50 MPH
      - Median crossing w/ braking from 35 – 45 MPH
    - Simulator tests:
      - Railway shipping
      - Haul away shipping in China
      - 4 post road simulations
      - 4 poster sine waves
  - Extreme low torque to turn ignition key condition tested
    - Physical tests with detent plunger and spring removed
    - <u>None of these tests resulted in unintended key rotation</u>

Fig 1A: Physics

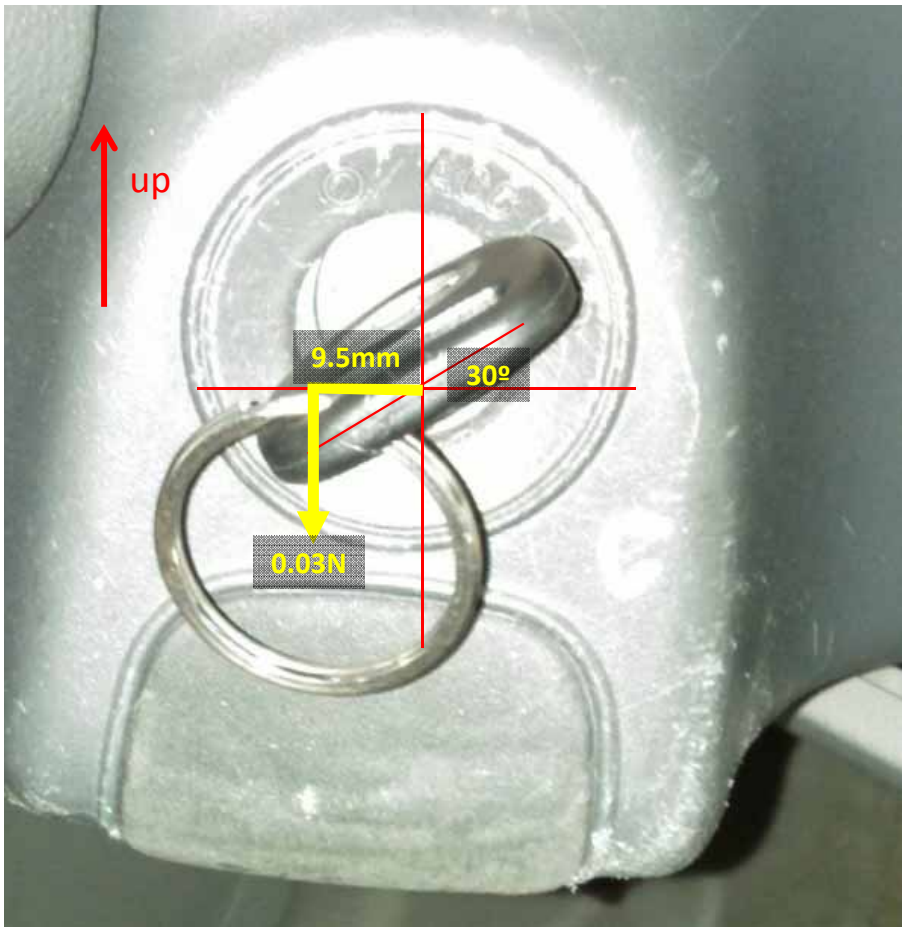
Input torque must exceed system resistance torque to cause rotation. Ignition switch torque is the primary component of the system resistance torque.

Input torque calculations:
Ring weight = 0.031 Newtons (0.007lb)
Slot length in key head = 2.2 cm
Moment arm = ½ slot length * cos 30º = 0.95 cm
Static torque = 0.031 N * 0.95cm = 0.03 N*cm

Input torque due to inertial forces is negligible with key and ring only.

Vertical "g" level	N*cm of torque generated
33	1
67	2
133	4
267	8
533	16

Table 1A



Physical Tests

Physical Tests - Vehicles

Make	Chevy	Saturn	Chevy	Pontiac
Model	Cobalt	Ion	HHR	Solstice
Model Year	2005	2007	2008	2006
VIN	1G1AK52F157562218	1G8AJ55F97Z111061	3GNDA33P88S0115EX	1G2MB33B36Y100151
Mileage	81624	104962	12020	9668

Table 2A – Vehicles tested

Physical Tests - Overview of Data Channels

Overview of Data Channels

Ignition Switch Signal Voltages, and digital message

Three analog voltages at the ignition switch were measured to determine switch state as shown in figure 2A .
All three voltage signals are read by the vehicle's Body Control Module (BCM). The BCM determines ignition state based on these voltages and sends a digital system power mode message. The system power mode message was also monitored in this testing.
The purpose of these measurements was:

1) Determine position of ignition switch.
2) Confirm that BCM was correctly interpreting ignition switch position.

In all cases the analog voltages matched the expected digital message.

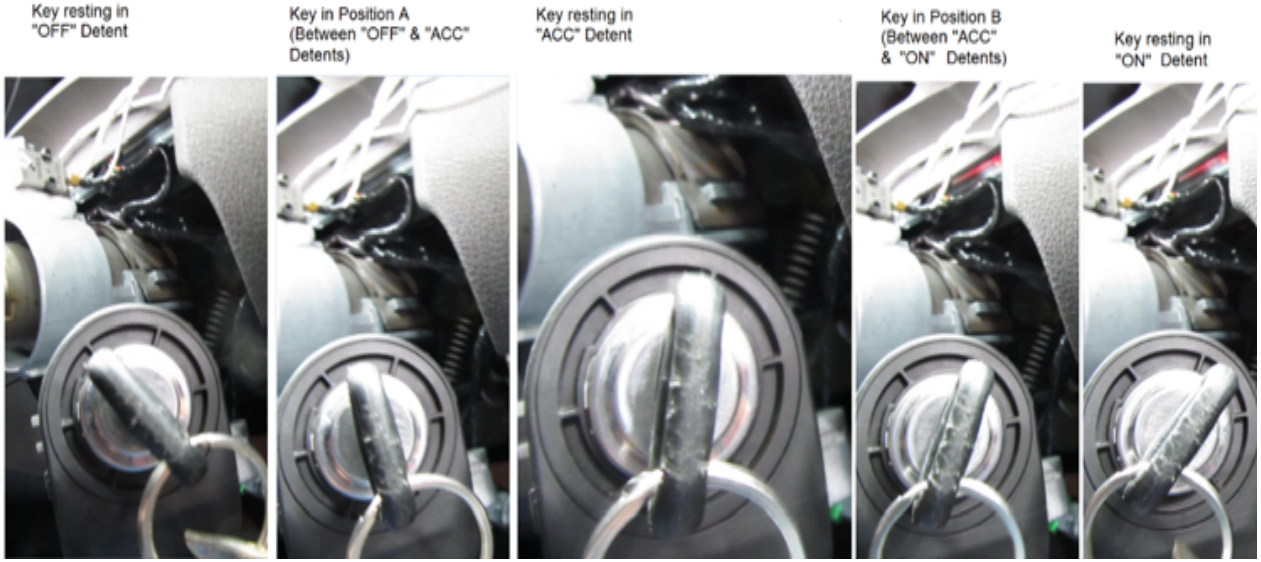


Figure 2A

Overview of Data Channels

Other data collected

- DC Tri-axial accelerometer mounted to steering col in proximity of ignition switch
- GPS based position and speed
- Event marker for synchronization to video

Physical Test Descriptions

All Physical Testing performed at General Motors Milford Proving Ground

Test Description

Belgian Blocks – Rough road test

- A replica of Belgian granite block roads that are very rough, including dips and bumps.

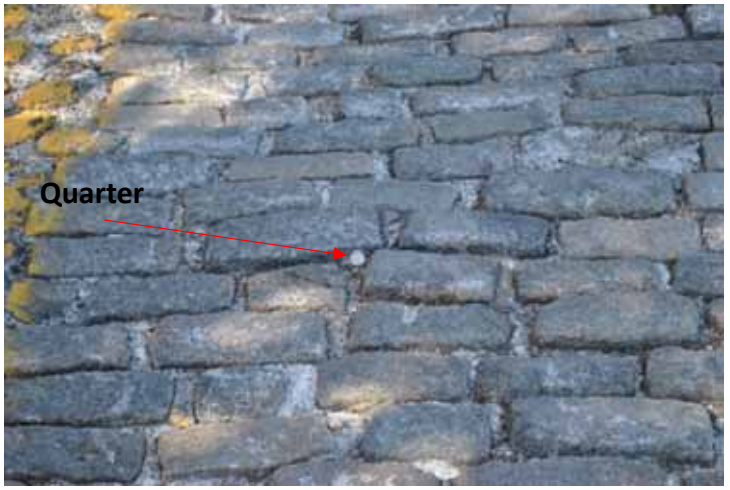


Figure 4C

Figure 4A

Figure 4B

Test Description

Severe Pothole Strikes

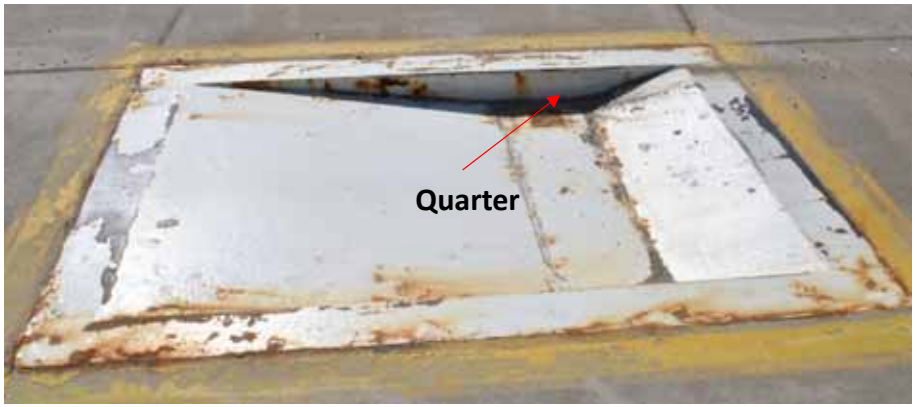


Figure 5A - Pothole 1

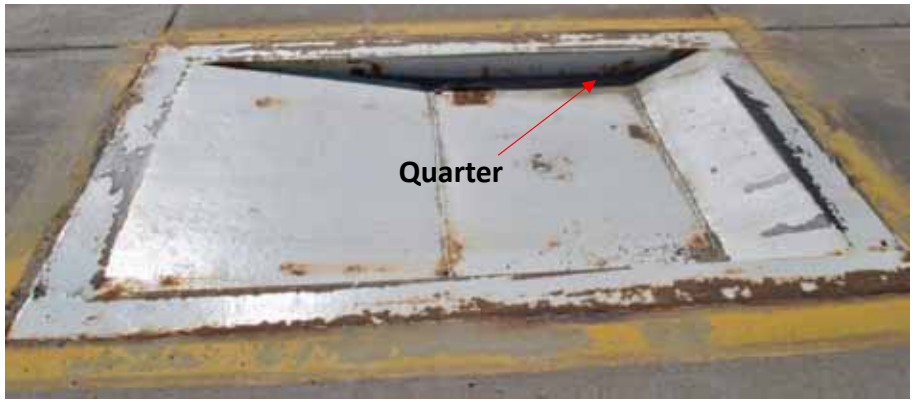


Figure 5B – Pothole 2

Test Description

Cubilete – High severity rough road

- A replica of a rough road in Mexico, made of river rocks
- Driven at 10 - 15 mph

Figure 6A

Test Description

Ride and Handling Loop

Chatter Bumps from 55 – 45 MPH – A series of evenly spaced bumps that excite suspension motion. Frequency (cycles per second) = mph /3

Figure 7A

Figure 7B

Ride & Handling Angled RR crossing @ 60 – 80 MPH - An elevated, railroad crossing that is at an angle to the road direction

Figure 7C

Test Description

Panic Stops

- Panic stops conducted on a smooth and level road surface.
- Consisted of light acceleration to speeds of 10 to 15 mph, followed by a full and rapid brake pedal application.

Test Description

Median Crossing

Driving between 15 and 50 MPH across wood platform simulating a median.
Driving between 35 and 45 MPH across wood platform simulating a median with a panic brake application when front wheels reach end of median

Median dimensions:
15 feet wide
12 feet long
4 inches tall

Figure 10A Median Crossing

Test Description

Median Crossing

- Median Crossing @ 50 MPH without Braking

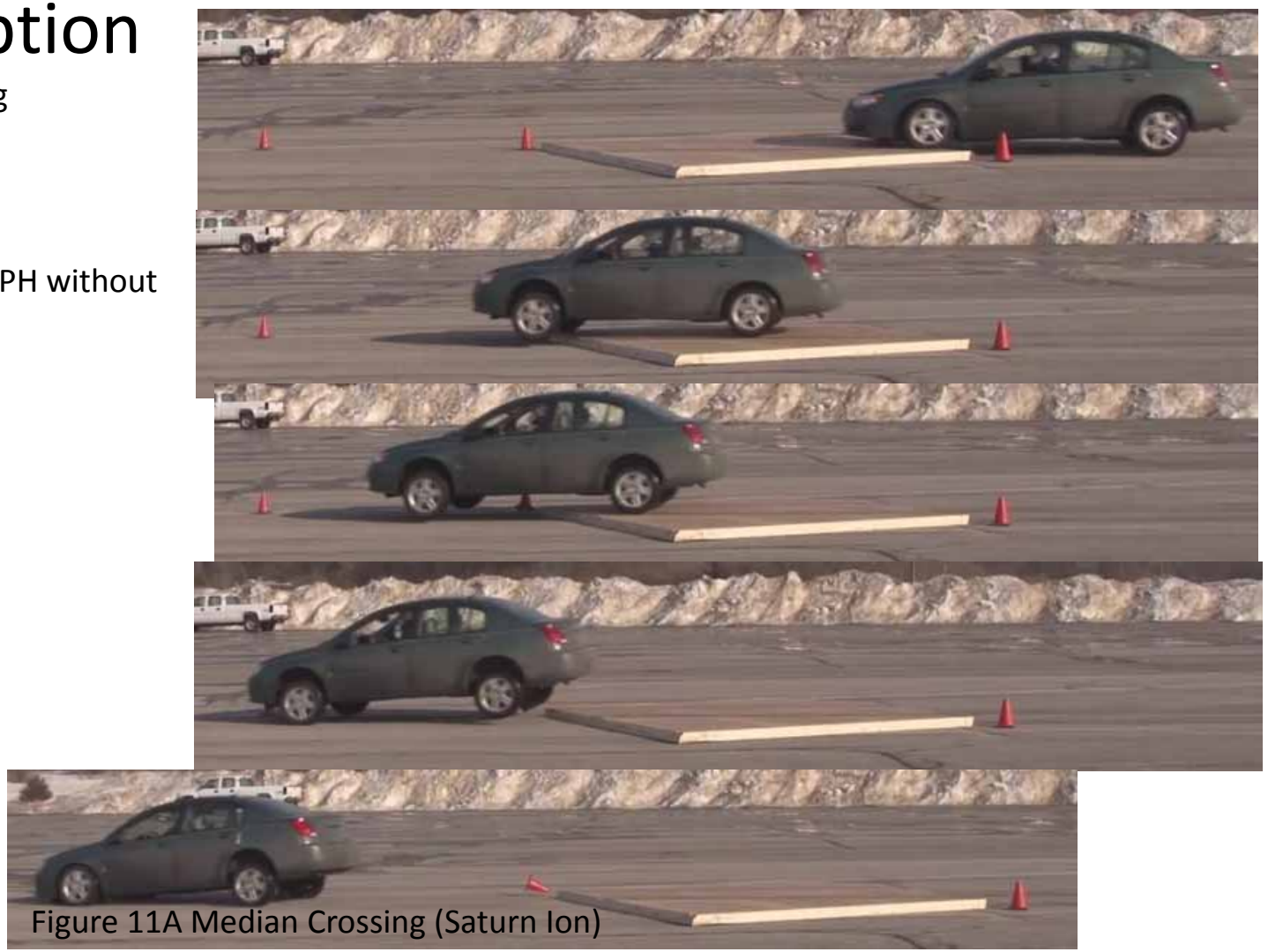


Figure 11A Median Crossing (Saturn Ion)

Test Description

Median Crossing

- Median Crossing @ 45 MPH with Braking

Figure 12A Median Crossing with Braking (Saturn Ion)

Test Description

Simulators - Shipping

Shipping simulator tests at Milford Proving Ground entail parking and tying down vehicle onto a hydraulic platform. These facilities provide repeatable simulation of motion encountered in severe shipping environments.

A repeatable simulation is played by computers into the controlling hydraulic cylinders to replicate severe conditions that have been measured in rail-car and truck haul away transportation of vehicles.

- Simulation of severe inputs from rail-car transportation
- Rail humps - simulation of vigorous fore-aft inputs into a transported vehicle during rail-car coupling.
- Simulation of severe inputs from truck haul away transportation.

Figure 8A Haul away simulator

Figure 8B Railway simulator

Test Description

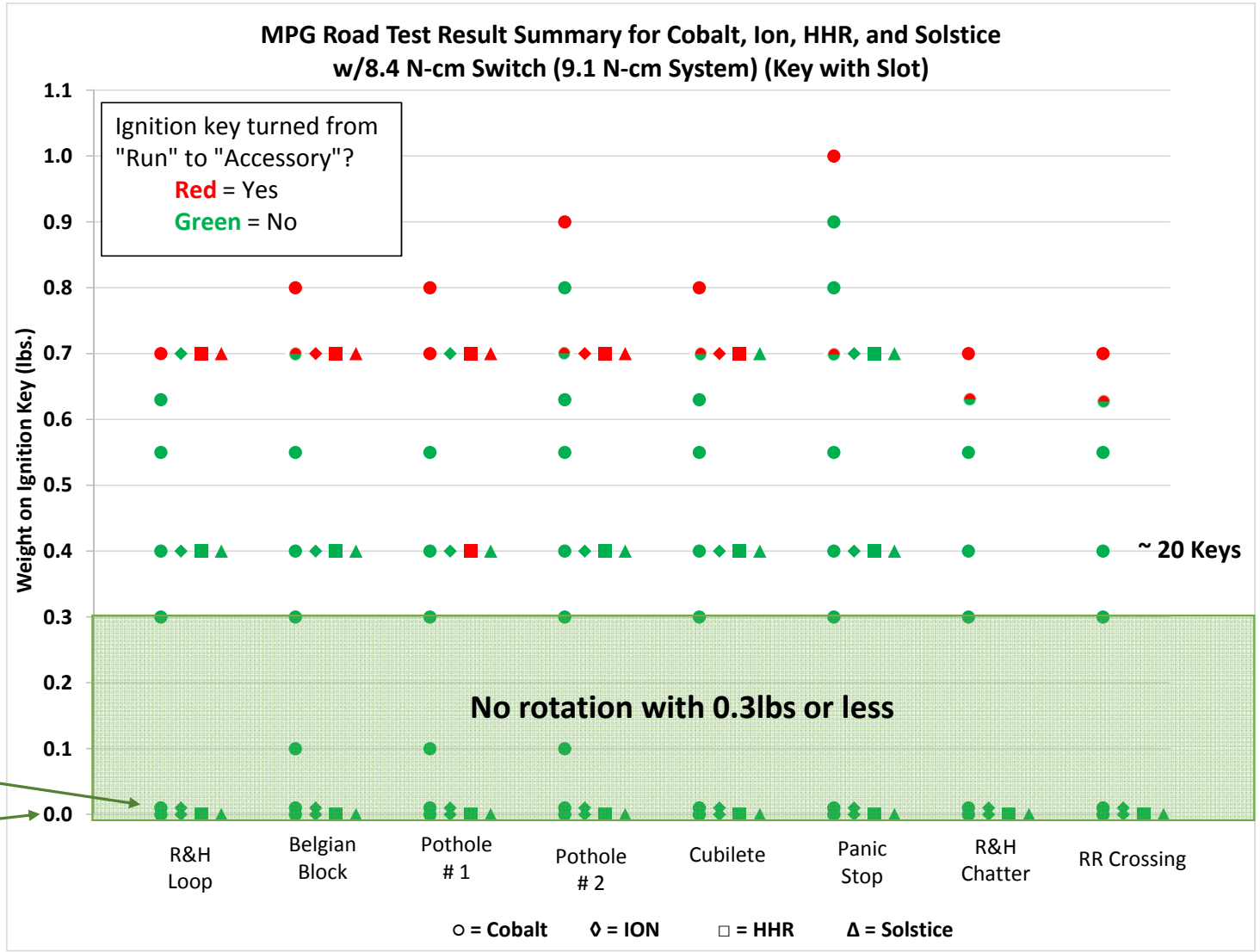
Simulators – 4 post road simulator

A 4-post roadway simulator where each wheel is on an individual hydraulic actuator was also used to evaluate unintended key rotation. This facility provides repeatable simulations of proving ground road surfaces into the 4 hydraulic cylinders generating independent vertical inputs into the vehicle's tire interface.

Figure 9A 4 post roadway simulator

Physical Tests - Results

Figure 13A test results for four different vehicles with common low torque (8.4 N*cm) ignition switch.



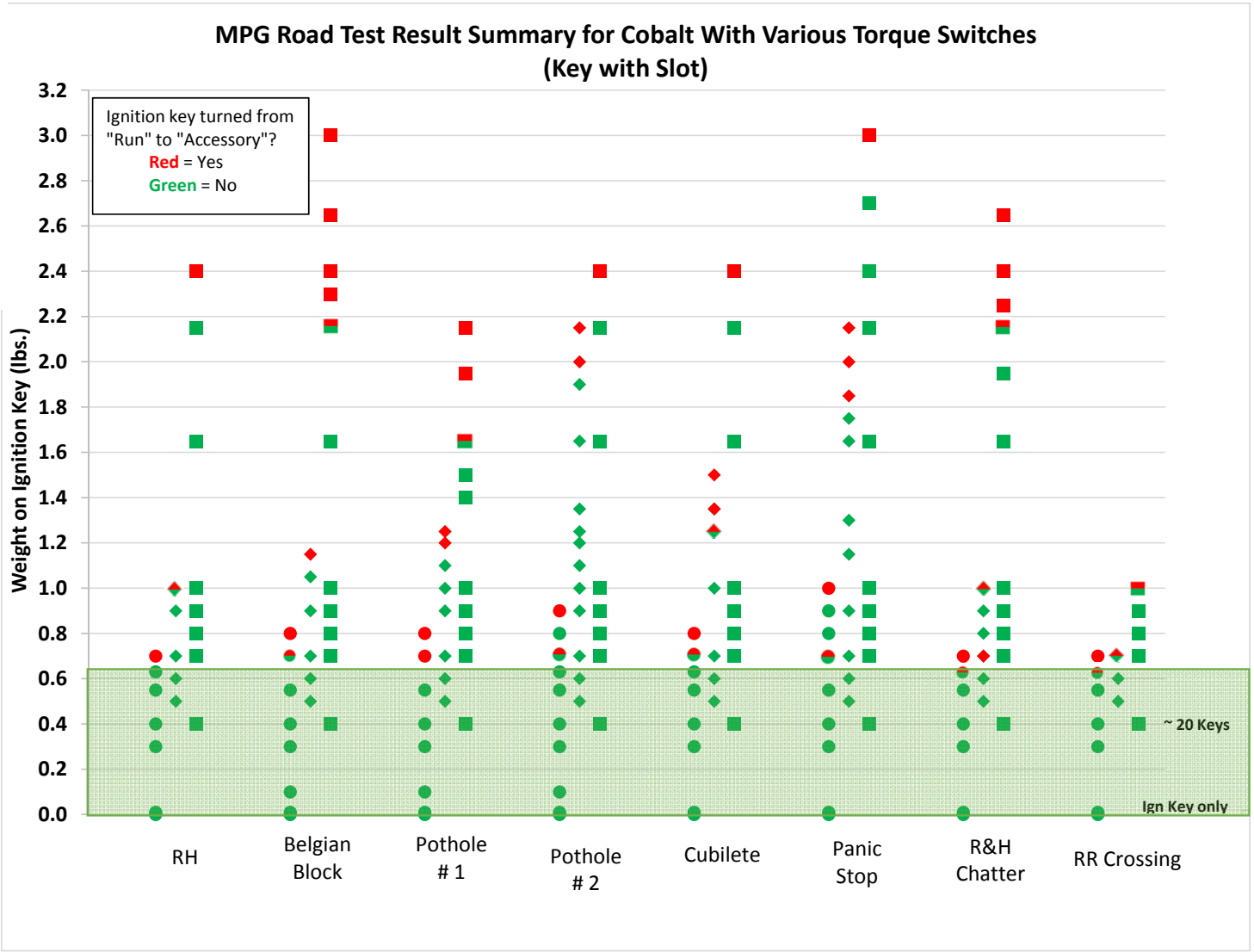
○ = **Cobalt**
◊ = **ION**
□ = **HHR**
Δ = **Solstice**

Typical house key weighs approximately 0.0175 lbs.

Empty Ring = 0.007lb
Ign Key Only = 0.0 lb

Figure 13A

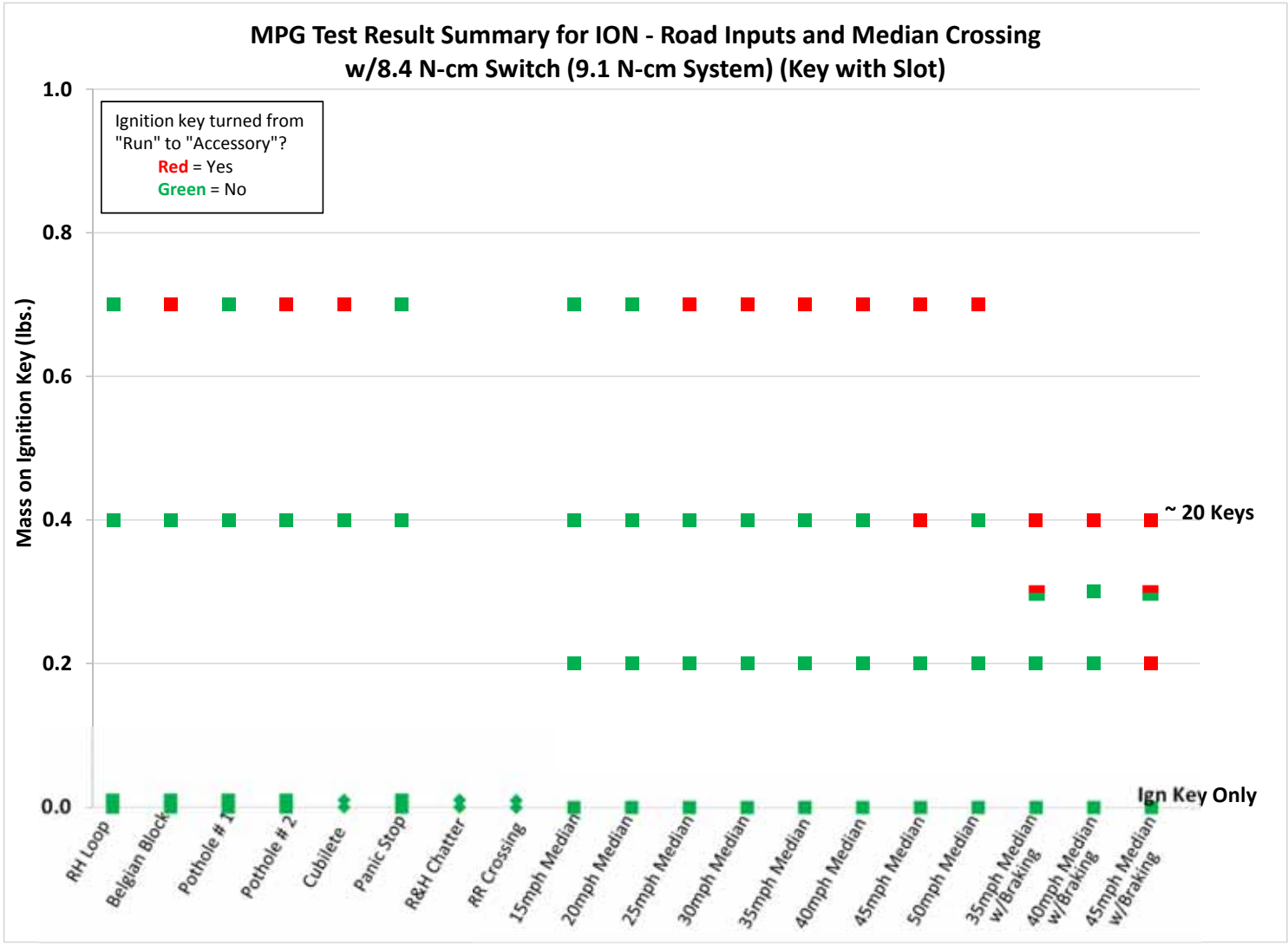
Figure 14A. Demonstrates increasing switch torque increases the weight required on ignition key to cause rotation



Switch Torque:
○ = 8.4 N-cm
◊ = 12.9 N-cm
□ = 20.3 N-cm

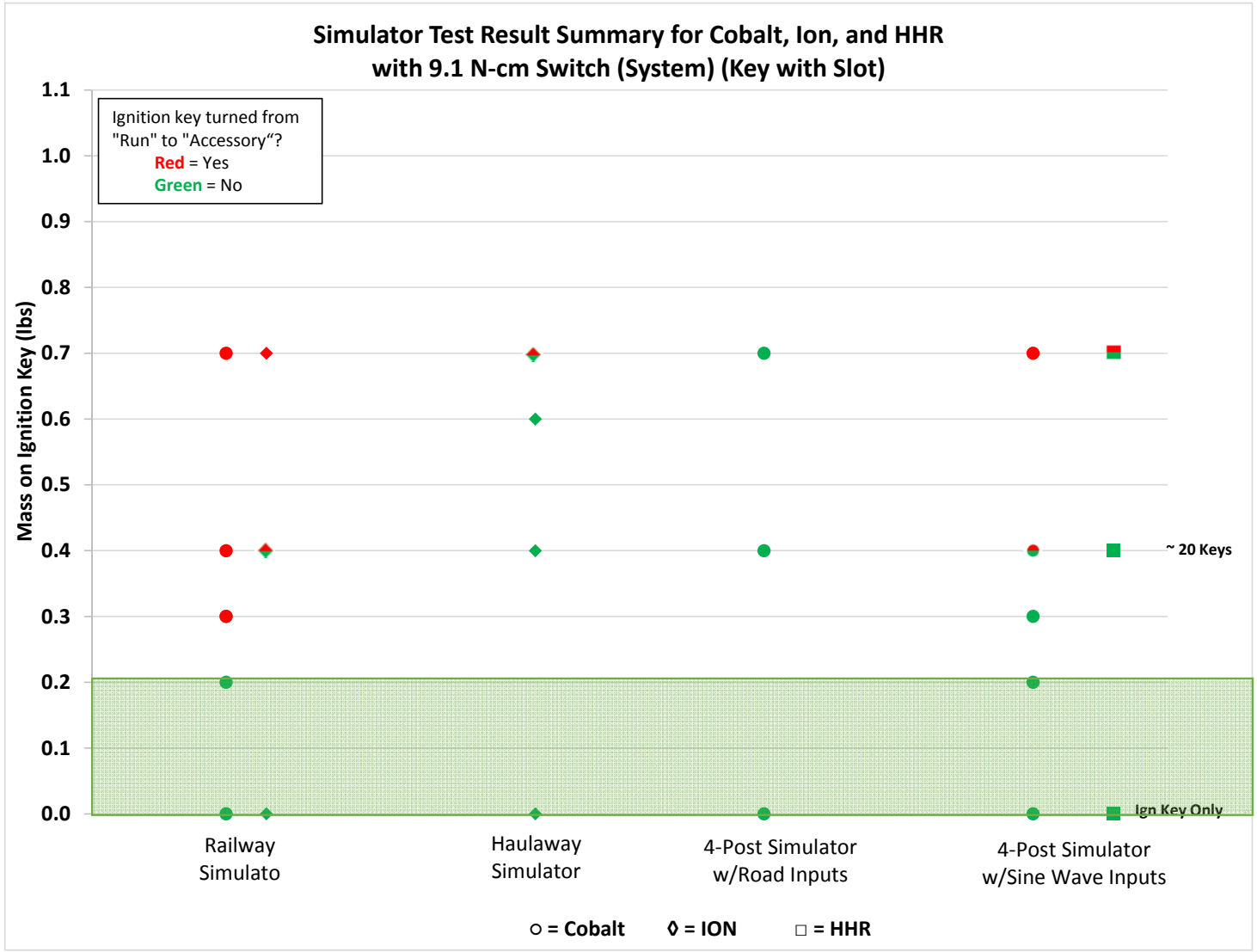
Typical house key weighs approximately 0.0175 lbs.

Figure 14A



Typical house key weighs approximately 0.0175 lbs.

Figure 15A



Typical house key weighs approximately 0.0175 lbs.

Figure 16A

Cobalt test results

Vehicle																
Switch	Switch #1 with Detent Plunger and Spring removed	Switch #2 with Detent Plunger and Spring removed	Cobalt w/ Cobalt 8.4 N*cm switch (9.1 N*cm system)													
Key	Slot	Slot	Slot													
Event	Key and Key ring	Key and Key ring	0.7# mass	1.0# of keys	0.9# of keys	0.8# of keys	0.7# of keys	0.63# of keys	0.55# of keys	0.4# of keys	0.3# mass 1.25# diameter	0.3# mass 2.5# diameter	15 Keys	10 Keys	Empty ring	0 keys
Ride and Handling loop @ posted speeds	409	410	36,127				210	159	153	35,126	391				399	47,48,125
Belgian Blocks durability schedule	409	410	33,105,106,136			307	216		156	32,103,104,135	396	34		101,102	406	49,50,134
Pothole #1	409	410	27,93,95,130			301	213		154	25,89,91,128	393	29,31		97,99	400	51,52,132
Pothole #2	409	410	28,94,96,131		303	302	214		155	26,90,92,129	394	30		98,100	401	53,54,133
Cubilete @ 10 MPH	409	410	41,42,122			300	209	157	151	37,38,123	390	39,40			397	45,46,124
Panic stop from 10 mph	409	410	43 44	306*	305*	304*	215		404	403	395				402	55,56
R&H Chatter @ 45 - 55MPH	409	410	57,58				210,212	160 158	152	61,63	391				398	59,60
R&H Angled RR crossing @ 70 mph	409	410	57,58				212	159,160 158	152	61,63	392				398	59,60
Median crossing @ 15 MPH																
Median crossing @ 20 MPH																
Median crossing @ 25 MPH																
Median crossing @ 30 MPH																
Median crossing @ 35 MPH																
Median crossing @ 40 MPH																
Median crossing @ 45 MPH																
Median crossing @ 50 MPH																
Median crossing w/ braking @ 35 MPH																
Median crossing w/ braking @ 40 MPH																
Median crossing w/ braking @ 45 MPH																
Railway 15 min Simulator			19							14,22		17	21	15,16,20		83
Rail Humps Sinulator																
China Haulaway truck simulator																
4 Poster road inputs			2							*No*						70,71,72,73,74,75,76,77,78,79,80,81
4 poster Sine wave			3							4,5,11,13 12			9,10	6,7,8		82

Numbers in cells correspond to individual data logger files in the respective vehicle's log

Red – indicates moved away from run

Green – indicates did not move away from run

No – indicates test was run without actuation, but only observational data was collected

* Pavement was damp and max decel was reduced

Cobalt test results - Continued

Vehicle	Cobalt																						
Switch	Cobalt w/12.9 N*cm (14.4 N*cm system)																					Cobalt w/ hand reworked 14.8 N*cm	
Key	Slot																					Slot	
Event	2.15#	2.0#	1.9#	1.85#	1.75#	1.65# of keys	1.5# of keys	1.35# of keys	1.3# of keys	1.25# of keys	1.2# of keys	1.15# of keys	1.1# of keys	1.05# of keys	1.0# keys		0.9# of keys	0.8# of keys	0.7# of keys		0.6# of keys	0.5# of keys	0.6# of keys	0.5# of keys
Ride and Handling loop @ posted speeds															323	322	321,324		258		253	243	174	163
Begian Blocks durability schedule												342		343			341		262		248	247	169	168
Pothole #1										329	333		331		327		325		259		249	244	170	165
Pothole #2	375	375	374			336		335		330	334		332		328		326		260		250	245	171	166
Cubilete @ 10 MPH							310,314,315	316	311	309,313,317					308,312				255		254	241	176	161
Panic stop from 10 mph	376	377		378	379	340			339			338					337		261		251	246	172	167
R&H Chatter @ 45 - 55MPH															323	318,322	321,324	320	256,257	319	252	242	173,174,175	162,164
R&H Angled RR crossing @ 70 mph															318			320	319	256,257	252	242	173,175	162,163,164
Median crossing @ 15 MPH																								
Median crossing @ 20 MPH																								
Median crossing @ 25 MPH																								
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Median crossing @ 45 MPH																								
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Cobalt test results - Continued

Vehicle																	
Switch	Cobalt w/ 20.3 N*cm switch (20.8 N*cm system)																
Key	Slot																
Event	3#	2.7#	2.65#	2.4#	2.3#	2.25#	2.15# (1.65# keys +	1.95# (1.65# of keys + 0.35 mass)	1.65# of keys	1.5# of keys	1.4# of keys	1.0# of keys	0.9# of keys	0.8# of keys	0.7# of keys	0.7# mass	0.4# of keys
Ride and Handling loop @ posted speeds				371, 385			352,353		345			206	195	190	179	146	141
Begian Blocks durability schedule	358		359	360	361		362 357		349			201	200	185	184	150	140
Pothole #1							354	364	365 346	367	366	202	197	186	181	148	138
Pothole #2				386			355		347			203	198	187	182	149	139
Cubilete @ 10 MPH				384			351		344			208	193	192	177	145	137
Panic stop from 10 mph	389	388		387			356		348			204	199	188	183	144	143
R&H Chatter @ 45 - 55MPH			370	371		372	352 369	368	345			205,207	194,196	189,191	178,180	147	142
R&H Angled RR crossing @ 70 mph												207 205	194,196	189,191	178,180	147	142
Median crossing @ 15 MPH																	
Median crossing @ 20 MPH																	
Median crossing @ 25 MPH																	
Median crossing @ 30 MPH																	
Median crossing @ 35 MPH																	
Median crossing @ 40 MPH																	
Median crossing @ 45 MPH																	
Median crossing @ 50 MPH																	
Median crossing w/ braking @ 35 MPH																	
Median crossing w/ braking @ 40 MPH																	
Median crossing w/ braking @ 45 MPH																	
Railway 15 min Simulator																	
Rail Humps Sinulator																	
China Haulaway truck simulator																	
4 Poster road inputs																	
4 poster Sine wave																	

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Ion, HHR, and Solstice Results

Vehicle	Ion													HHR			Solstice		
Switch	Ion original switch (9.1 N*cm system)						8.4 N*cm switch removed from Cobalt							8.4 N*cm switch removed from Cobalt			8.4 N*cm switch removed from Cobalt		
Key	Slot						Slot							Slot			Slot		
Event	0.7# mass	0.6# of keys	0.4# of keys	0.3# mass	keychain and fob	0 keys	0.7# mass	0.4# of keys	0.3 lb 2.5"	0.3 lb 1.25"	10 keys	Empty ring	0 keys	0.7# mass	0.4# of keys	0 keys	0.7# mass	0.4# of keys	0 keys
Ride and Handling loop @ posted speeds	12,13		10	11		58	66	64				134	67	7	8	9	11	10	9
Begian Blocks durability schedule	6		2,3	4,5		56	75	74				139	76	16	17	18	21	19	18
Pothole #1	7		9	8		54	70	72				136	68	14	12	10	16	14	12
Pothole #2	26		141			55	71	73				137	69	15	13	11	17	15	13
Cubilete @ 10 MPH	16,17,33,35	18,19,20,21	14	15	22,23	36,37	62	63				133	61	6	5	4	8	7	6
Panic stop from 10 mph	30,31,32	29	142			143	78	80				138	77	21	20	19	24	23	22
R&H Chatter @ 45 - 55MPH						144						135	140			42			34
R&H Angled RR crossing @ 70 mph						144						135	140			42			34
Median crossing @ 15 MPH							82	83			84		85						
Median crossing @ 20 MPH							89	88			87		86						
Median crossing @ 25 MPH							90	91			92		93						
Median crossing @ 30 MPH							97	96			95		94						
Median crossing @ 35 MPH							98	99			100		101						
Median crossing @ 40 MPH							105	104			103		102						
Median crossing @ 45 MPH							106	107			108		109						
Median crossing @ 50 MPH							113	112			111		110						
Median crossing w/ braking @ 35 MPH								118	116	117	119		120,121						
Median crossing w/ braking @ 40 MPH								124	126	125	123		122						
Median crossing w/ braking @ 45 MPH								130	127	128,129	131		132						
Railway 15 min Simulator	45,46		47,50,51 48,49			53													
Rail Humps Sinulator	44																		
China Haulaway truck simulator	39 42,43	41	40			52													
4 Poster road inputs																			
4 poster Sine wave														25,29,31 22,24,27,30	32,33	36,37			

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Extreme low torque ignition switch condition tested with key and ring only

- Physical vehicle tests performed with detent plunger and spring removed
  - Detent plunger and spring provide primary source of torque to resist key rotation
  - With these parts removed, the resulting switch torque due to internal friction only and is very low (1.3N*cm). Key rotates without the ability to tactically discern ignition key state.

Detent plunger and spring removed

Figure 17A

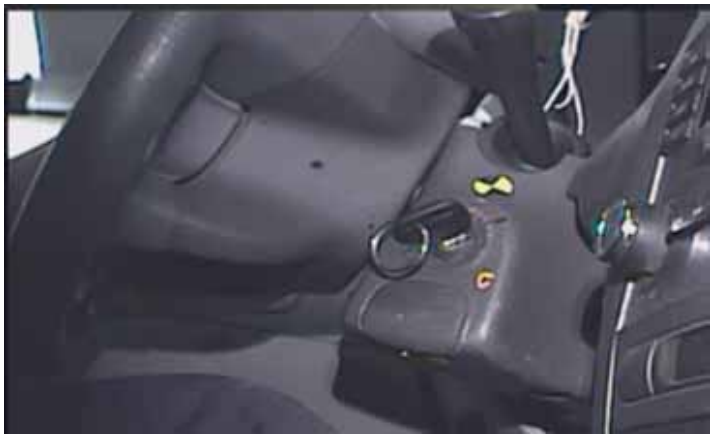

Figure 18A

Extreme low torque ignition switch condition tested with key and ring only

- Physical vehicle tests with an empty key ring involving extreme maneuvers on severe road surfaces were performed with ignition switch that had detent plunger and spring removed
- ***Test results show no incidents of unintended key rotation.***
  - Confirms physics prediction that input moment is negligible with key and ring only

2005 Cobalt with ignition switch modified to remove detent plunger and spring	
Event	**Ignition key rotation from run to accessory?**
Ride and Handling loop @ posted speeds	***No***
Begian Blocks durability schedule	***No***
Pothole #1 @25 MPH	***No***
Pothole #2 @ 25 MPH	***No***
Cubilete @ 10 MPH	***No***
Panic stop from 10 mph	***No***
R&H Chatter @ 45 - 55MPH Hz=MPH/3	***No***
R&H Angled RR crossing @ 70 mph	***No***

Conclusions

- A series of tests at GM's Milford Proving Ground involving extreme maneuvers on severe road surfaces as well as on full vehicle simulators demonstrated unintended key rotation could occur when sufficient weight was attached to the key ring.

- In any test event where unintended key rotation occurred with weight attached to the key ring, the test was repeated with nothing on the key. Over 80 tests were repeated with only the ignition key or ignition key and empty key ring. These test results show no incidents of unintended key rotation.

- An additional 16 tests were conducted with the ignition switch detent plunger and spring removed resulting in very low (~1 N*cm) resistance torque. Test results show no incidents of unintended key rotation when only an empty key ring was attached to the ignition key.