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The importance of Robust Design Methodology -

Case study of the infamous GM ignition switch recall

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Abstract: A systematic quality strategy is of crucial importance for the success of manufacturing companies. At the same time, the universal applicability and effectiveness of implemented quality management practices were called into question by a number of major product recalls in recent years. This article seeks to illustrate how already simple analyses and early stage design methods can help to better understand one of the potential reasons for these failures, namely the variation inherent in manufacturing, assembly, and use processes. While usually thoroughly controlled in production, it seems as if particularly the risk of unanticipated coinciding variation effects remain largely underestimated and thus unaccounted for in design practice, sometimes with disastrous consequences.

To foster the awareness of this variation and to illustrate the benefits of its early consideration in product development, this paper reviews one of the most infamous recalls in automotive history, that of the GM ignition switch, from the perspective of Robust Design. It is investigated if available Robust Design methods such as sensitivity analysis, tolerance stack-ups, design clarity, etc. would have been suitable to account for the performance variation, which has led to a number of fatal product defects and the recall of 30 million vehicles. Furthermore, the disclosed legal case files were examined, offering a unique opportunity to examine how technical malfunctioning of the ignition switch could stay undetected long enough to result in fatalities.

Keywords: Root Cause Analysis, Failure Diagnosis, Robust Design, Tolerances

1. Introduction

The popularity of quality management practices, such as Total Quality Management (TQM), Six Sigma, or Lean Manufacturing (e. g. Chiarini 2011), reflects the importance that a systematic and purposeful quality strategy has for companies. In addition, there is a wide consensus that a purely production-focused quality strategy, relying exclusively on process control and continuous improvement activities in manufacturing, is not sufficient to keep pace with today’s stringent quality requirements for increasingly complex products (Batchelor 2010, Booker 2012). On the contrary, quality has to be systematically designed into products as well as continuously monitored and optimized using design methods and available Computer Aided Engineering (CAE) tools. In light of this quality-by-design idea, companies have spent a lot of time and money to widen their quality initiatives and to complement their production-focused quality management practices by additional design approaches (Gremyr & Hasenkamp 2010).

However, the establishment of a quality mindset and the way towards an efficient quality management system in design appears to be difficult and cumbersome for many companies. On the one hand, literature points to a number of technical and organisational challenges that companies are facing during an implementation of quality practices (Krogstie et al. 2014, Booker 2012). On the other hand, the confidence in the effectiveness of already implemented methods and tools is regularly undermined by major product recalls, e. g. recently launched by big automotive OEMs. At the same time, even in the case of a product recall the majority of manufactured products performs according to specifications. Usually, only a small percentage malfunctions, and even fewer failures have safety critical effects. This leads to the question of what the technical root causes for these randomly occurring quality issues are, of why they could not be predicted by the implemented design analyses, testing protocols, or quality control procedures respectively.

In academia as well as industrial practice, there is little disagreement that one essential task to ensure a consistent product behavior and a predictable lifetime without failures, is to systematically account for the influence of variation inherent in manufacturing, assembly, and use processes (Taguchi 2005, Thornton 2004, Ebro and Howard 2016). Over the last decades, this insight has led to the emergence of well-accepted and widely implemented variation-focused design methodologies, such as Robust Design (Taguchi 2005), Variation Risk Management (Thornton 2004) or Design for Six Sigma (Chowdhury 2002).

At the same time, literature points however to a mismatch between the existing awareness for variation and the actual use of corresponding methods and tools. Given the tremendous list of potential variation influences on increasingly complex products as well as the complexity of many statistical analysis tools (Thornton 2000, Gremyr et. al 2003), the time-to-market pressure frequently takes precedence (Thornton 2004). Many of the available quality practices consequently implicate the risk that an analysis only focusses on common, hence already-known and predictable, variation sources in late design stages, while unanticipated variation-effects are not taken into account systematically. These unfavorable coincidences of tolerances, load scenarios, and/or noise factors are instead mitigated by safety factors, late design changes, and excessive inspection, still prevalent in industrial practice (Ebro et al. 2014) and potentially still necessary to prevent non-conforming products to reach the market.

Therefore, the aim of this article is to further foster the awareness for variation and to illustrate the benefit of a methodical analysis of variation by means of early stage design methods. For this purpose, the article presents a review of one of the most infamous recalls in automotive history, that of the General Motors (GM) ignition switch, from the perspective of Robust Design (RD). A number of available early-stage RD methods and tools are used in order to identify how coinciding variation influences could contribute to a number of fatal product failures and a sweeping recall. In addition, the legal case files have been examined, illustrating a number of insights about design/management decisions impacting the resulting robustness of the ignition switch, hence its inconsistent performance in the field.

In *section 2*, the paper opens with a discussion of the GM Ignition Switch case from a technical as well as managerial point of view. *Section 3* then provides the necessary background knowledge on different research areas in the field of Robust Design Methodology, before the results of the investigation into the effects of variation are presented in *section 4*. Afterwards, *section 5* summarizes how unaccounted variation could have contributed to the fatal consequences, before a conclusion is presented in *section 6*.

2. The GM Ignition Switch – a forensic engineering case

This paper refers to the case of the faulty GM ignition switch. After several severe accidents, the case had led GM to launch one of the most infamous recalls of automotive history in the first half of 2014. In total, the recall covered more than 30 million vehicles and resulted in a $ 900 million deferred-prosecution agreement, as well as a maximum possible fine of $ 35 million over GM's delayed response to the defects.[1] As the corresponding investigation by the federal authorities also included the disclosure of numerous documents, the GM ignition switch case offers a unique possibility for this

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[1] Reuters (16.09.2015) "GM to pay $900 million, settle U.S. criminal case over ignition switches." http://www.reuters.com/article/us-gm-probe-idUSKCN0RG2WF20150916, [Accessed 12.07.2016].

paper's purpose. The following section presents the available information sources on the case and introduces the switch's functionality.

2.1. Analysis of the ignition switch – a reverse engineering approach

Both, the very scarce academic publications (Shaout and Dusute 2014, Jennings and Trautman 2015) and the case files of the congressional hearings, have so far focused largely on the legal responsibility and liability with little emphasis on design error. Hence, they are evidently incomplete from a design perspective. For this reason, three different sources of information were used to gather the necessary technical details for an evaluation of the switch design:

(1) **Case files:**
The document binders, which were made accessible as part of congressional hearings on the website of the Committee on Energy and Commerce (United State House of Representatives).

(2) **Internal GM-Report:**
An internal report on the ignition switch recall by the law firm Jenner & Block, which was made available in a redacted version (Valukas 2014) in the course of the federal investigation.

(3) **Set of 11 physical samples:**
A full CAD model of the ignition switch was reverse engineered from a physical switch sample, which was ordered from a spare part supplier in 2014. Subsequently, nine similar replacement parts (model year 2014), shown in Figure 1 (a), as well as one used Chevrolet Cobalt steering column assembly (model year

2005), shown in Figure 1 (b), could be acquired to determine if there is geometric variation between different switch samples.[2]

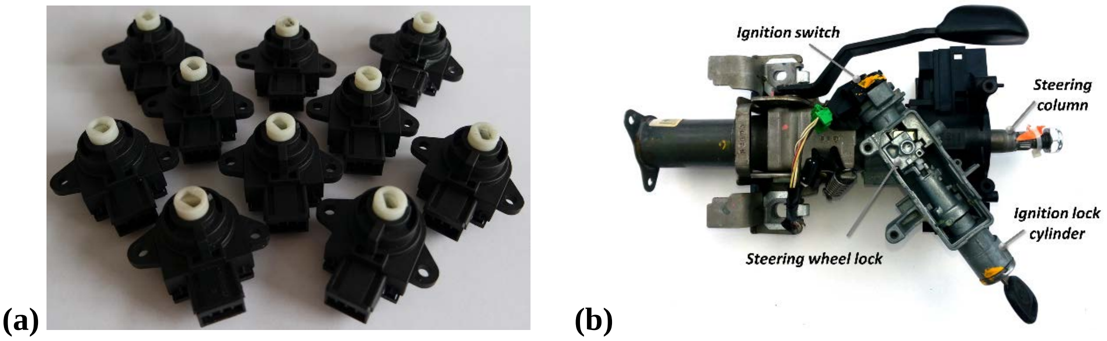

Figure 1. Set of ignition switches consisting of (a) 10 service replacement parts and (b) one sample from a steering column assembly.

2.2. *The ignition switch's catastrophic failure mode*

According to various media reports, crash scene investigators had identified that on several GM models involved the ignition key was found on the ACCessories position.[3] The conclusion was drawn that the likely cause of the crashes was the unintentional slipping of the key from ON to ACC position, leading to the shutdown of the engine, the airbags, the power-assisted steering as well as the power brake unit. The component at the root of the problem was identified as the commonly used ignition switch, shown in Figure 1 (a). Attached to the steering column, the switch becomes coupled to the steering wheel lock, the ignition lock cylinder, and consequently to the key as shown in Figure 1 (b). Its main purpose is to convert the rotational movement of the key into a signal, which is sent to the Body Control Module defining the actual power mode of the engine

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[2] The sample, which could be acquired for this research, is obviously far from being representative. Nevertheless, the available physical products offered a valuable first impression on geometric variation of switch components as well as the difference between model years.

[3] e. g. Rogers, A. (16.05.2014) "GM to pay record $35 million fine over ignition switch recalls." http://time.com/102906/gm-fine-ignition-recalls/, [Accessed 12.07.2016].

and the vehicle’s accessories.

The switch’s basic functionality is revealed by a closer look to its internal components and the structure of the relevant interfaces between them, see Figure 2 (a). In an essentially mechanical concept, the key is used to manually rotate the *switch plate* in order to define the position of the connected *contact pins* relative to the *circuit board*, see Figure 2 (b). The actual contact areas on the circuit board in turn define the resulting signal sent to the Body Control Module. As feedback to the driver, the ignition switch furthermore has two steady modes, which sit between the OFF and the START positions. These indexing positions, ON as well as ACC, are defined by notches in the *switch plate* and are active when the spring loaded spring/*plunger* assembly is forced into these notches, locking the mechanism until the key is turned, see also Figure 2 b).

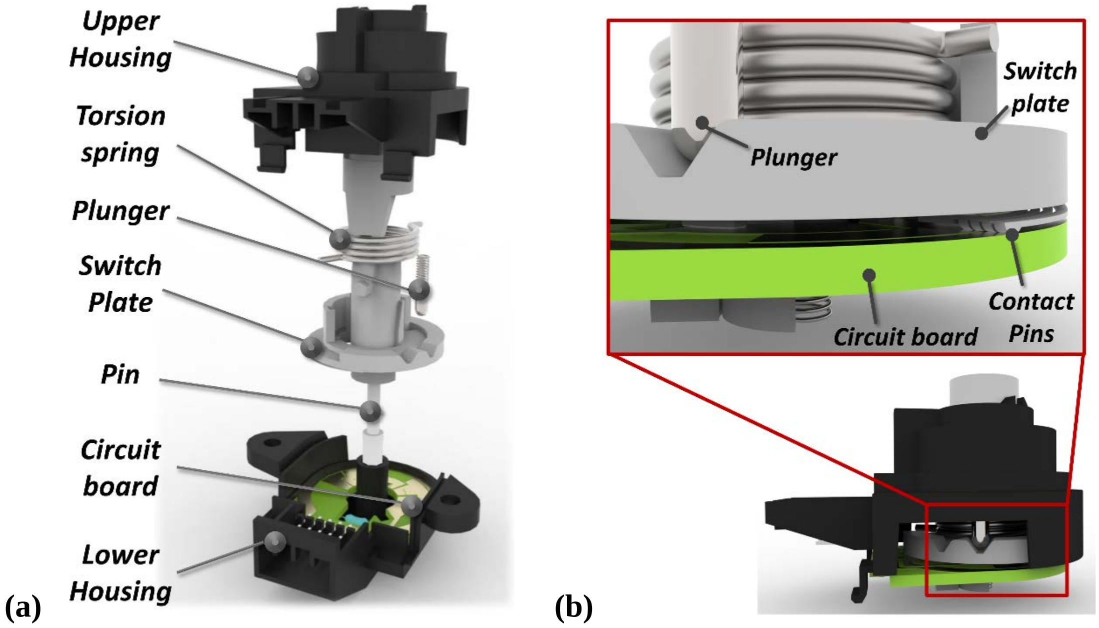

Figure 2. Detailed view on (a) the structure of the ignition switch as exploded CAD view and (b) the function-relevant interface.

To start the vehicle’s engine, the driver has to turn the key and thus the switch plate to the START position from where it has to return back to its ON position after ignition. The required force for this backwards movement is provided automatically by a *torsion spring* mounted to the switch plate. On the side opposite to the notches, the spring engages with a surface on the *upper housing* when the switch plate passes the ON towards the START position, see Figure 3.

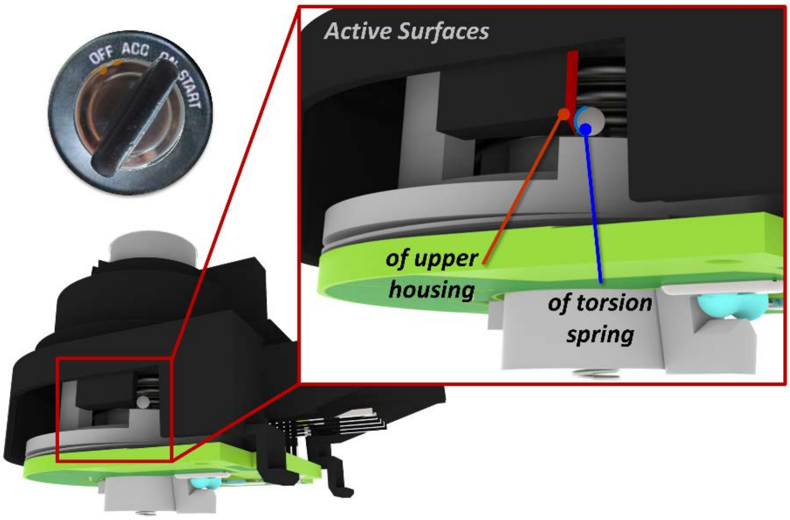

Figure 3. Contact surface between torsion spring and the upper housing.

2.3. Development of the ignition switch - a managerial perspective

As laid out above, the unpredictable malfunctioning of ignition switches after reaching the market suggests that unanticipated or underestimated variation-effects are one of the reasons for the later product recall. However, corresponding variation influences are commonplace within product development practice and usually identified and successfully mitigated by a sequence of rigorous analyses carefully conducted tests, and quality control procedures. In order to provide some background knowledge on why corresponding technical issues in this case went undetected long enough to result in fatalities, this section briefly summarizes some key numbers of a GM internal investigation, which focused on "*the circumstances that led up to the recall (…) due to the flawed ignition switch*" (Valukas 2014).

Since the ignition switch was designed and produced to an agreed requirements specification by the supplier Delphi, there were major failings by both companies (Valukas 2014). At the same time, misjudgements and errors were not restricted to the development process alone, but as summarised in Table 1 also prevalent in the organisation and management of change, being one of the major reasons for GM’s delayed response to detected failures.

Table 1: Procedural and managerial failures in the ignition switch case

	Issue	**Explanation**
Development process	**Lack of respect for torque specification given the switch’s failure history**	*“Validation testing conducted by Delphi in late 2001 and early 2002 revealed that the Ignition Switch consistently failed to meet the torque values in the Specification”.* (Valukas 2014, p. 45) But *“given the switch's history of electrical failures […] [the responsible engineer] was hesitant to make any changes that might jeopardize the switch’s electrical architecture. Because he believed the Ignition Switch had performed properly and without incident during the numerous vehicle-level test conducted on the prototype Ion, […] [he] approved production of the switch - even though the switch's torque was below the Specification”.* (Valukas 2014, p. 49-50)
	Incorrectly diagnosed failure modes	*“Engineers ignored reports of the moving stall problem, considering them a "duplicate" [of a previous crank/start caused by how the grease reacted in cold weather] - even though they were very different issues with completely different causes. Consequently, the low torque problem went unaddressed, even though now it was causing moving stalls.”* (Valukas 2014, p. 57)
	Loss of functional overview within the system	*“None of the engineers, with one exception […], involved in the Problem Resolution and Tracking System process who had primary responsibility for the functioning of the Ignition Switch, understood that loss of power would prevent the airbags from deploying. […] Their failure to understand how the Ignition Switch interacted with the airbags, a part of the car for which they did not have oversight or responsibility, was a significant factor in the failure to resolve the switch problems in a timely fashion.* (Valukas 2014, p. 64-65)
	Culture of silence and non-action	*“There was resistance or reluctance to raise issues or concerns in the GM culture. If an employee tried to raise a safety issue […], the employee would get pushback. And Mary Barra explained that problems occurred during a prior vehicle launch as a result of engineers being unwilling to identify issues out of concern that it would delay the launch.”* (Valukas 2014, p. 252)
Organisational	**Ad hoc approach to issue resolution**	The *“Ignition Switch issue passed through an astonishing number of committees”*, where engineers *“flagged the issue, proposed a solution, and the solution died in a committee or with some other ad hoc group exploring the issue. But determining the identity of any actual decision-maker was impenetrable. No single person owned any decision.”* (Valukas 2014, p. 255)
	No notes at safety meeting approach	*Although without official instruction, “a number of GM employees reported that they did not take notes at all at critical safety meetings because they believed GM lawyers did not want such notes taken.”* (Valukas 2014, p. 254)

Particularly noteworthy, as perhaps the most damning of all, was furthermore the decision of the responsible engineer to allow for changes to the parts without a formal design change record! As shown in Figure 4, the spring/plunger assembly was increased in length numerous times from 10,6 mm to 12,2 mm over the years. While the “*change to the spring in the Ignition Switch changed the part’s function*” (Valukas 2014, p. 100), and while the responsible engineer “*did not seek authorization of the Change Approval*

Board to proceed with the same part number" (Valukas 2014, p. 101), this decision stayed without consequences.

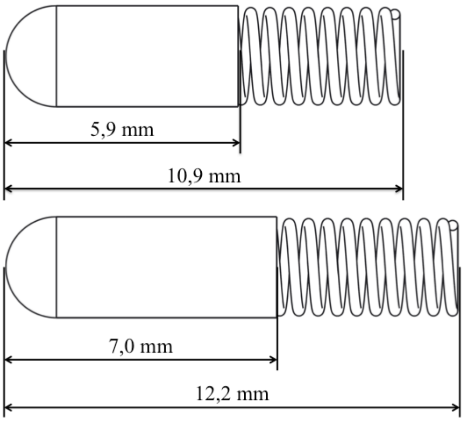

Figure 4. Change in spring/plunger length

3. Robust Design Methodology

Historically, RD originates from Taguchi's Quality Engineering framework (Taguchi 2005), which was proposed in the late 1950s and popularised by its implementation in the US in the 1980s. While Taguchi's basic idea of an experimental Robustness optimisation has consequently received most of the attention in academia and practice (Jugulum 2007), RD research has evolved into a variety of different fields over the last decades.

First of all, it should therefore be noted that the majority of traditional contributions on Robust Design focus largely on the optimisation of robustness based on controlled experiments (e. g. Taguchi 2005 or Phadke 1989). Providing a widely acknowledged, variation-focused design philosophy, the corresponding approaches are consequently relying on an existing (preliminary) solution, and despite their indisputable benefits neglect the disproportionately large impact of early design decisions (Jugulum 2007).

In order to overcome these limitations, several research contributions have placed increasing emphasis on the implementation of RD principles for the identification of robust product concepts (Jugulum 2007, Andersson 2007) and/or their embodiment into robust preliminary solutions. The latter is of particular interest for the purpose of this paper, as corresponding RD principles for a quick assessment of unambiguous interfaces (Ebro et. al 2012), as well as methods for the design of exact constraints (Blanding 1999) or optimal locations schemes (Söderberg et al. 2006) are essential to achieve robustness of products and processes. As already specified by seminal work on engineering design (e.g. Pahl and Beitz 2007), overconstrained design solutions, ambiguous interfaces between components, unfavourable material combinations, etc. are largely susceptible to variation and therefore frequently experience production/ assembly issues, reduced performance, excessive and non-predictable wear-rates, etc.

An overview of corresponding approaches for the systematic analysis and design of robust products in early design stages can for example be found in Eifler et al. (2014) or Gremyr et al. (2003). Although not claimed to be exhaustive, the given set is considered as a good basis for choosing corresponding RD approaches in the following.

4. Analysis of the ignition switch case from a Robust Design perspective

While there is little disagreement about the relevance of variation in product development, the potential benefits of an early consideration of Robustness by means of simple methods and tools are frequently less well accepted. Therefore, an exemplary set of early stage RD methods is used to prioritise the potential contributing factors in case of the GM ignition switch. The investigation is structured into two steps:

(1) ***Functional perspective:*** an analysis of the switch’s functionality.

(2) ***System perspective:*** systematic consideration of components and interfaces

For a first critical review, all results were furthermore continuously compared with the available set of 11 switch samples and triangulated with the information in the case files. Table 2 provides an overview of the variables used to describe the ignition switch's functionality and its characteristics in the following.

Table 2: Nomenclature table

Symbol	SI	Description	Symbol	SI	Description
$\boldsymbol{F_s}$	N	Spring force	$\boldsymbol{r}$	mm	Dist. plunger to switch's rotation axis
$\boldsymbol{F_N}$	N	Normal force at the contact surface	$\boldsymbol{\theta_{ON,ACC}}$	rad	Measured notch angle (ON to ACC)
$\boldsymbol{F_R}$	N	Friction force at the contact surface	$\boldsymbol{\theta_{ACC,OFF}}$	rad	Measured notch angle (ACC to OFF)
$\boldsymbol{F_{v,h}}$	N	Resulting forces at contact surface	$\boldsymbol{F}$	N	Holding force of locking mechanism
$\boldsymbol{\mu}$		Coefficient of friction	$\boldsymbol{T_{ON,ACC}}$	Ncm	Measured torque level
$\boldsymbol{\theta}$	rad	Notch angle (steepest)	$\boldsymbol{\hat{T}_{ON,ACC}}$	Ncm	Estimated/calculated torque level
$\boldsymbol{s}$	mm	Compression of spring in groove	$\boldsymbol{h_1}$	mm	height of the lower housing shell
$\boldsymbol{k}$	N/mm	Spring constant	$\boldsymbol{h_2}$	mm	height of the upper housing shell

4.1. Functional perspective - analysis of the ignition switch's functionality

The first step of the analysis is to link potential failure modes of the ignition switch to a description of its basic functionality by creating a simplified analytical model, i. e. the *governing equation*. Based on the underlying physical principles, this model is used for a first prioritisation of relevant Design Parameters (DPs) by means of a sensitivity analysis, which is then compared to measurements of the available switch samples.

4.1.1. Potential failure modes

To identify potential failure modes in (complex) products, authors from different research fields (Bertsche and Lechner 2008, Andersen and Fagerhaug 2006) commonly refer to the same qualitative approaches. Although a corresponding Failure Mode and Effects Analysis (FMEA) was also performed during the development of the ignition switch (Hearing, 2014b), the analysis was clearly unsuccessful. On the one hand, the responsible Delphi engineers only referred to the force of the detent spring, shown in Figure 4, as single root cause for a potential "*overshooting*" of the detents (Hearing, 2014b). On the other hand, corresponding information was furthermore not considered safety critical in the course of the subsequent development activities, as detailed in GM's internal investigation (see also section 2.3).

4.1.2. Key quality characteristics and governing equation

An essential step of every variation-focused analysis is the identification of key characteristics (KCs), i. e. "*a quantifiable feature of a product or its assemblies, parts or processes whose expected variation from target has an unacceptable impact on the cost, performance, or safety of the product*" (Thornton 2004). A corresponding prioritisation of part KCs can for example be based on a simple mathematical model of the product's basic functional principle, referred to as *governing equation* hereinafter.

As laid out in the sections above, the basic safety-related functionality of the ignition switch, i. e its locking mechanism, is an essentially mechanical concept. A preloaded spring/plunger assembly is forced into notches in the switch plate, holding it in defined positions to determine the power modes of the vehicle. Although extremely simplified, the locking mechanism can consequently be described in terms of friction forces at the engaging surface of plunger and notches based on Coulomb's law of friction for the purpose of this paper, see Figure 5. The spring force F_s, the corresponding normal force F_N respectively, leads to a friction F_R at the contact surface. Only if the applied force F exceeds the resulting horizontal force F_h, and also enables the necessary compression of the spring F_v, the plunger disengages so that the switch can change position.

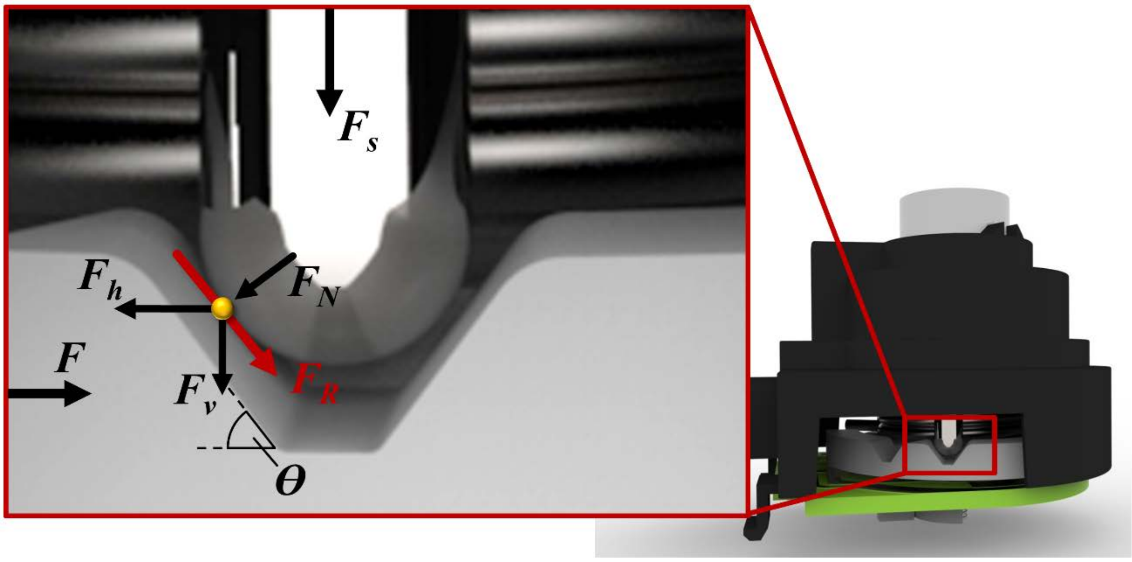

Figure 5. Deriving a governing equation for friction at the contact surface

The corresponding mathematical formulation of the necessary force F in equation 1 summarizes the different DPs affecting the locking mechanism, i. e. the friction coefficient μ, the angle of the notches θ as well as the spring force F_s comprising of compression s and spring coefficient k.

$$F = f(r, \theta, \mu, k, s) = k \cdot s \; \frac{\tan\theta + \mu}{1 - \mu \cdot \tan\theta} \qquad (1)$$

4.1.3. Sensitivity Analysis

The assessment of parameter sensitivity is a further essential task in a variation-focused analysis (Saltelli et al. 2009). Numerous methods for this *Sensitivity Analysis* exist, which differ significantly in terms of complexity as well as computational costs, see for example reviews by Frey and Patil (2002) or Borgonovo and Plischke (2016). At the same time, research also provides corresponding metrics for specific applications such as the prioritisation of design parameters in early design stages (Hutcheson and McAdams 2012) or the quantification of robustness (Göhler et al. 2016a).

As the available case files do not provide any design information, the expected values and variation windows of the considered DPs had to be identified in a reverse engineering approach, see for example k_0, s_0, θ_0 and μ_0 in Figure 6 (a). Given that the investigation furthermore refers to a beforehand defined, largely simplified mathematical model, a simple nominal-range based sensitivity index was deemed most suitable for the purpose of the analysis. With this one-factor-at-a-time approach, the sensitivity of the desired system performance is calculated by the ratio of the changing system output to a given percentage change of one input variable, while all other influences are kept constant. Calculated based on the derived governing equation, Figure 6 (b) plots the corresponding deviation of the holding force ΔF in dependency of a ±5% change of the input variables and illustrates the particular importance of the notch geometry. An angle variation significantly increases the resulting variation of the holding force $F(\Delta\theta)$ and moreover does not show a linear influence. At the same time, it has to be noted though that realistic variation values are necessary for a meaningful assessment of the parameter's relevance. Therefore, all results are verified based on measurements of the switch's geometry in the following section.

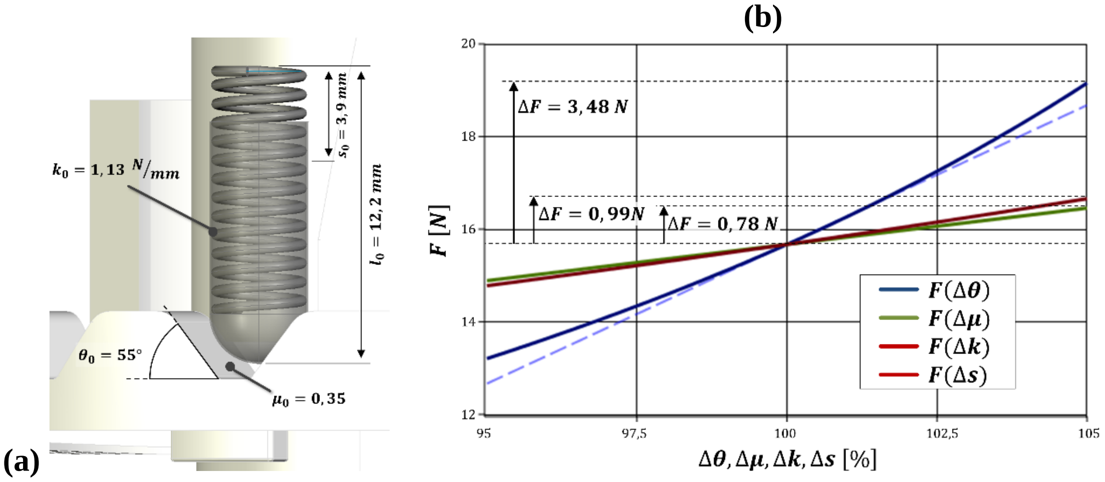

Figure 6. Importance of variation around the (a) given nominal values for DPs derived in a (b) scaled, derivative-based sensitivity calculation.

4.1.4. *Initial verification of results*

The initial verification of results focusses on the impact of geometric variation on the ignition switch's basic functionality. The objective is to:

(1) underpin or refute the relevance of the notch geometry.
(2) to assess the applicability of the extremely simplified governing equation.
(3) to clearly delimit variation-effects from any potential engineering errors.

The verification consists of an optical measurement of the corresponding switch plates by means of optical scanning equipment, i. e. a *3Shape D800*® scanner with an accuracy of $15\,\mu m$, which were post-processed and analysed with the 3D inspection software *GOM Inspect*. As illustrated in Figure 7, the corresponding measurement results are twofold. A noticeable variation not only occurs between the different switches, see Figure 7 (a), but could also be shown for the two notches on one physical sample as shown by Figure 7 (b). While the angle between ON and ACC position $\theta_{ON,ACC} = 53{,}4°$ was significantly lower as the angle between ACC and OFF position $\theta_{ACC,OFF} = 55{,}5°$, the comparison with additional switch plate samples led to an even wider variation window of the notches, that is a range of $\theta_{ON,ACC} \in [53{,}3°\,;\,57{,}7°]$.

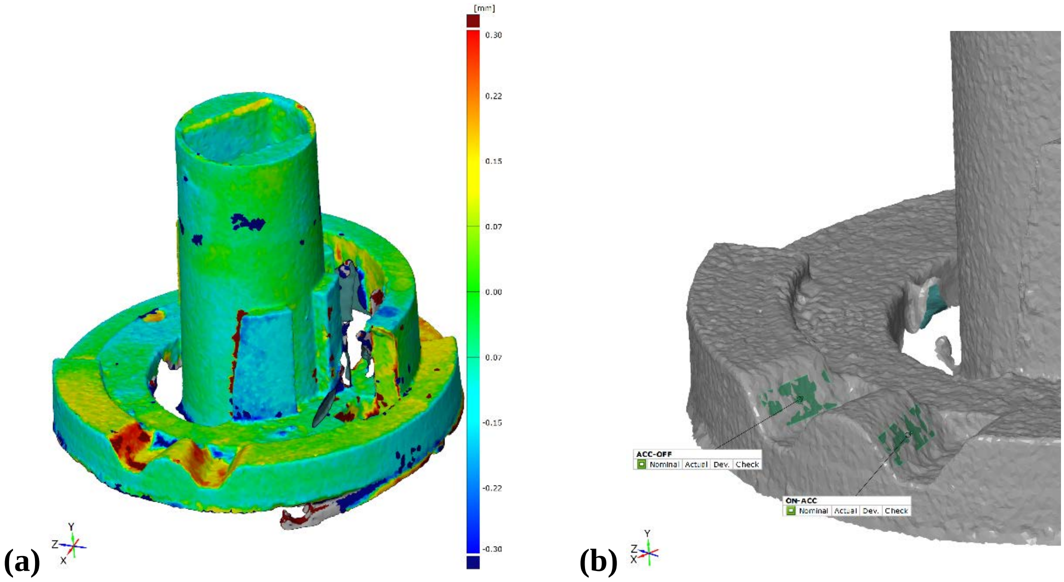

Figure 7. Optical measurement for a surface comparison of (a) service replacement parts (model year 2014) and (b) used ignition switch (model year 2005)

This rough estimation corresponds with results of analyses, which were previously conducted by different parties during the recall. As revealed by GM’s internal investigation, “*torque tests reported in 2002 showed […] [that] torque values to rotate* *from Run to Accessory ranged from as low as* 4 Ncm *or* 5 Ncm *up to* 11 Ncm" (Valukas 2014, p. 50). The switch's performance was consequently far from the specified requirement of 20 ± 5 Ncm, necessary to knock the key out of its ON position (Valukas 2014, p. 39). See also the measurements of a 2006 Chevrolet Cobalt model from an investigation of fatalities (Hearing 2014c) adopted in Figure 8.

Despite this huge variation in performance, GM seems however to have focused exclusively on a "*change to the spring […] 'to be in specification according [to] the GM spec for the torque forces'* " (Valukas 2014, p. 98). In contrast, neither GM's internal investigation nor the legal case files provide evidence that the switch design was altered to control or mitigate variation, which is still present in the new replacement parts as shown by the rough measurements above.

The available performance measurements given in Figure 8 furthermore show that the rough estimation of a minimum torque level $\hat{T}_{ON,ACC} = 10{,}61$ Ncm, calculated in the governing equation with a shallower notch angle $\theta_{ON,ACC} = 53{,}3°$, a changed spring length $l = 10{,}6$ mm, and the distance of the plunger from the switch plate's rotation axis $r = 12{,}8$ mm, falls below the reported varying performance of switches in the field. As shown by the magnified view of the torque necessary to rotate the key from the ON (72° rotation) to the ACC (47° rotation) position, the estimated range of the torque level $\hat{T}_{ON,ACC} \in [10{,}61\text{ Ncm}\,;\ 14{,}4\text{ Ncm}]$ is considerably lower than the measured variation window $T_{ON,ACC} \in [4\text{ Ncm}\,;\ 11\text{ Ncm}\,]$ reported by Valukas (2014).

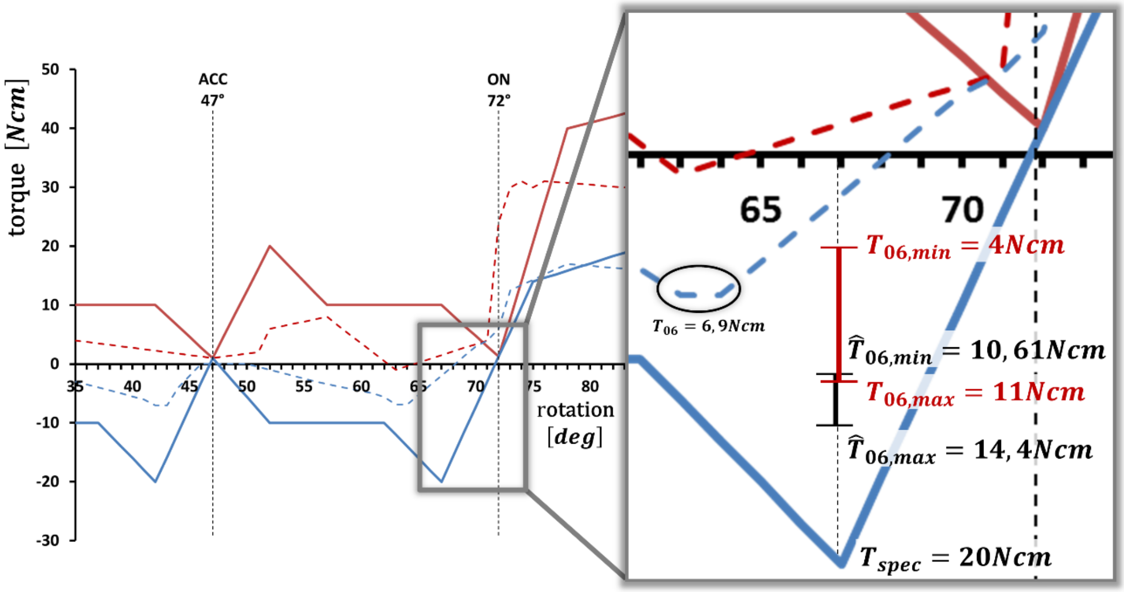

Figure 8. Comparison of specified key torque $\boldsymbol{T_{ON,ACC}}$ and its resulting variation, adopted from Hearing (2014c).

4.2. System perspective - analysis of the switch's parts and interfaces

A simplified description of a product's functionality, e. g. in form of the above derived governing equation, usually neither captures the large number of parts, nor their mating situation. This system perspective is covered in the next section through a calculation of linear/ dimensional tolerance stack-ups, a characterisation of interfaces between parts, a brief review of geometric tolerances as well as a verification of results.

4.2.1. Linear tolerance stack-up

With reference to the governing equation, the spring compression s is predominantly determined by the linear tolerance chain $D = A - B + C$ in axial direction. Consequently, the resulting torque is affected by the variation of 7 dimensions on the rotating *switch plate*, the static (*upper* and *lower*) part of the *housing* indicated in Figure 9, as well as the *spring/plunger* assembly itself.

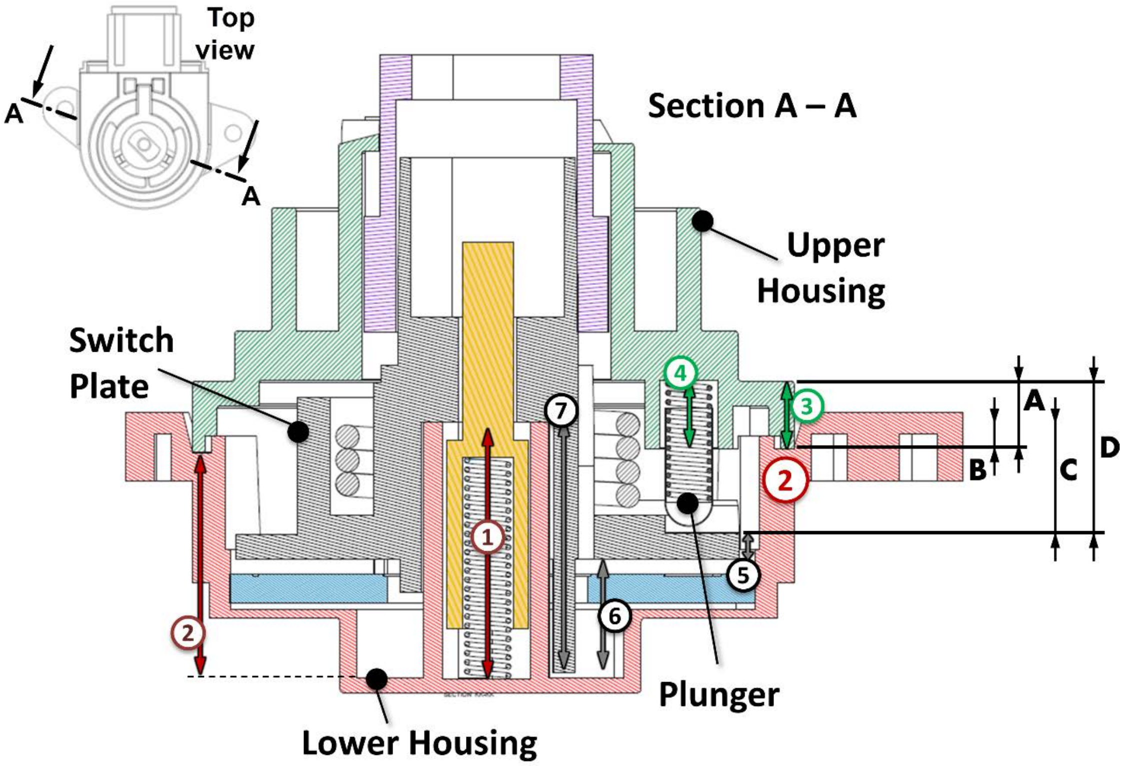

Figure 9. Function-relevant linear tolerance chain for the ignition switch.

For a prediction of the distance variation ΔD, an estimate for the potential production tolerances of each dimension was taken from the standard SPI (1998) describing the accuracy of injection molding processes as shown in Table 1.

Table 3: Estimated variation for contributing dimensions

Dimensions						Tolerance	
Name		Material	#	Feature type	Size	Comm. ±	Fine ±
Housing	lower	Polyoxymethylen / Acetal	*Dim* 1	Hole depth	16,50 mm	0,105 mm	0,075 mm
			Dim 2	Depth	12,40 mm	0,120 mm	0,065 mm
	upper		*Dim* 3	Depth	3,30 mm	0,105 mm	0,050 mm
			Dim 4	Hole depth	6,00 mm	0,105 mm	0,050 mm
Switch Plate		Polyamide / Nylon	*Dim* 5	Wall thickness	1,60 mm	0,130 mm	0,075 mm
			Dim 6	Depth	7,00 mm	0,100 mm	0,035 mm
			Dim 7	Hole depth	15,00 mm	0,130 mm	0,100 mm

Table 2 shows the results of the conducted tolerance stack up analysis. The calculation of the Worst-Case (WC) stack of *commercial* tolerances adds up to a $\Delta\widehat{D} = \pm 0{,}795$ mm. Given constant values for all other parameters in equation 1 (model year

2005), the assumption of coinciding worst cases for all tolerances consequently results in a torque range of $\hat{T}_{ON,ACC}(s \pm \Delta s) \in [7{,}74\ \mathrm{Ncm}\ ;\ 15{,}92\ \mathrm{Ncm}]$. Even a statistical Root Sum Square (RSS) calculation with an accuracy of $\pm\ 3\ \sigma$, i.e. an estimation met by 99.7% of the assemblies, leads still to a substantial torque interval of $\hat{T}_{ON,ACC}(s \pm \Delta s) \in [9{,}39\ \mathrm{Ncm}\ ;\ 14{,}26\ \mathrm{Ncm}]$.

Table 4: Calculation of tolerance stack-up

			Tolerance stack up			
			Comm. ±		**Fine ±**	
Dimensions		**[mm]**	**linear**	**RSS**	**linear**	**RSS**
A	*Dim 4*	6,0 mm	0,210		0,100	
B	*Dim* 1 – *Dim* 2	4,1 mm	0,225		0,140	
C	*Dim* 7 – *Dim* 6 – *Dim* 5	6,4 mm	0,360		0,210	
Total D		**8,3 mm**	**0,795**	**0,474**	**0,450**	**0,271**

The calculations once more illustrate why the measures taken by GM are particularly worrying from a RD perspective. An increased compression of the spring/plunger assembly in no way helps to reduce the occurring variation effects. Despite an increasing torque level, the model year 2014 is consequently still subject to the exact same window of performance variation $\hat{T}_{ON,ACC}(s \pm \Delta s) \in [15{,}97\ \mathrm{Ncm}\ ;\ 24{,}14\ \mathrm{Ncm}]$, barely acceptable given the specified tolerance for the switch's torque $\pm\ 5$ Ncm.

4.2.2. Interface Analysis

Linear tolerance stack ups, like above, largely simplify the complexity of mating conditions between components by neglecting form variation and the design of the mating interface itself. At the same time, poor surface design, otherwise termed a lack of *Interface Clarity*, has been pointed out as a substantial contributor to the overall variation in assemblies by RD literature (Ebro et al. 2012, Söderberg et al. 2006).

A clearly defined interface should have as few contact points as possible that are ideally small and positioned to maximise the assembly's robustness (Ebro et al. 2012). However, these basic principles of *Interface Carity* were largely disregarded in case of the ignition switch. An example are unclear location features and the additionally large contact surfaces, i. e. more potential contact points then necessary, between upper and lower housing, see Figure 10 (a). The same holds true for the connection between housing and switch plate as well as between the switch assembly and the steering column, see Figure 10 (b) and (c). The ambiguous interfaces lead to unpredictable mating conditions, hence an inherently complex and inaccurate variation analysis, and a product which is highly sensitive to variation.

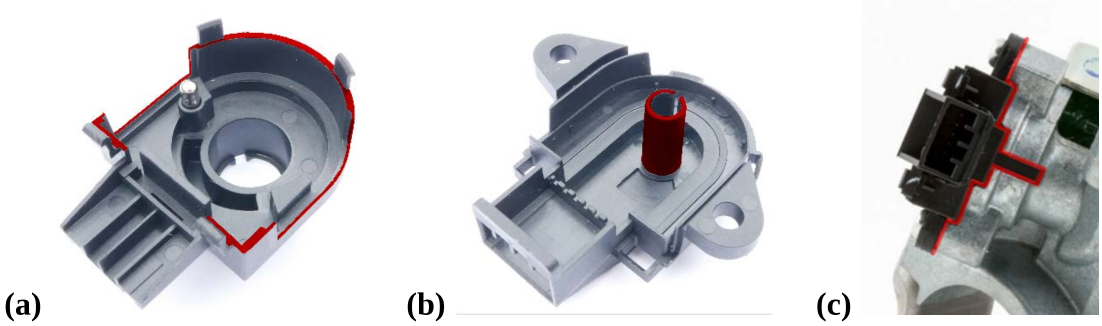

Figure 10. Large contact surfaces between (a) upper and lower housing, (b) lower housing and switch plate, and (c) switch assembly and steering column.

4.2.3. Analysis of geometric tolerances

Given the fact that there are no obviously identifiable connection points, , several scenarios were defined for the unclear mating conditions of the switch's components and calculated with the dimensional management software *RD&T (Robust Design & Tolerancing)*. Figure 11 (d) illustrates three examples of these analyses, which are based on independently varying contact points on the large contact surfaces between components (assumed to be normally distributed with a capability of $C_p = 1$).

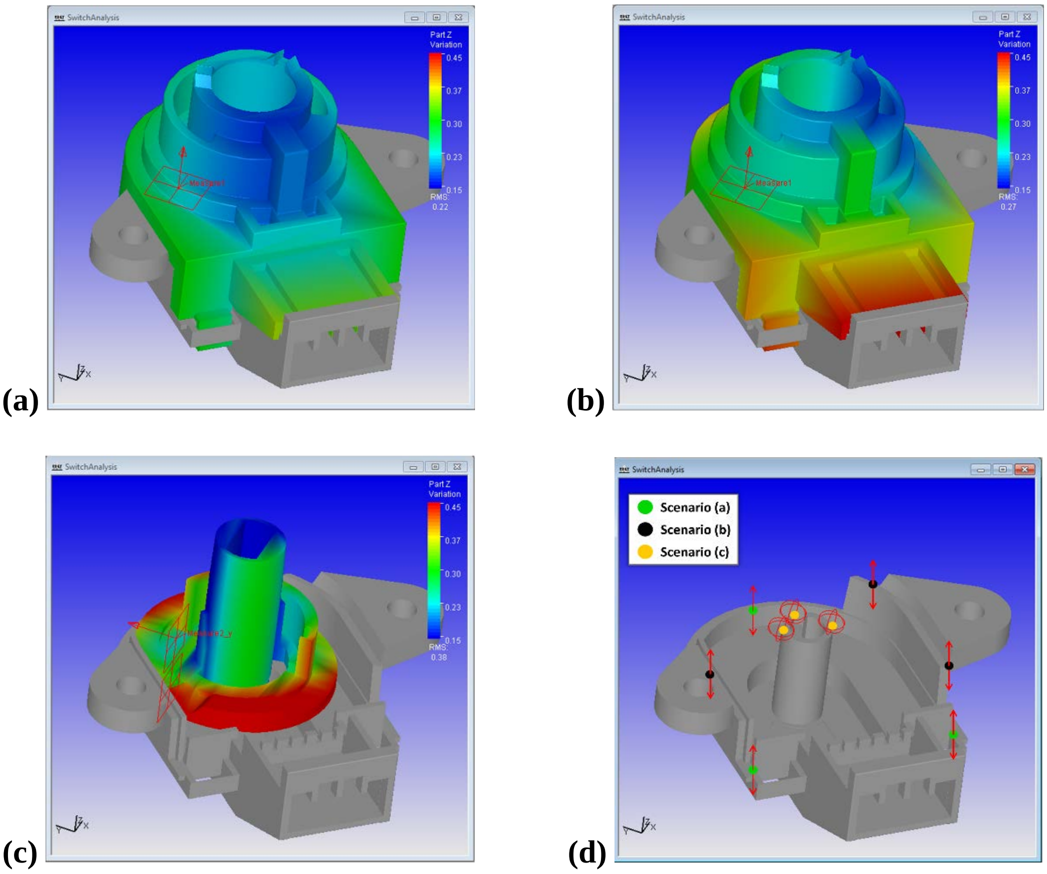

Figure 11. Simulation of tolerances in a (a) robust, (b) non-robust and (c) extended positioning system based on the in (d) specified mating scenarios.

The first scenario refers to a robust 3-2-1 positioning system between the two housing shells, i. e. locating points spread far apart with a variation and varying according to the flatness tolerance (Comm. $\pm 0{,}28$ mm) given in SPI (1998). As indicated by the results in Figure 11 (a), the effect of this approximated flatness tolerance appears to be of secondary importance. The displacement of the active surfaces between housing shells in vertical direction, indicated by the red *Measure*, results in 99,73% of the parts within $\Delta s = \pm 0{,}11$ mm for the spring compression. In the worst case, this corresponds to a torque change of $\Delta\hat{T}_{ON,ACC}(\Delta s) = \pm 0{,}57$Ncm, which is furthermore only marginally increased by the change to a non-robust positioning scenario, leading to $\Delta s = \pm 0{,}12$ mm and $\Delta\hat{T}_{ON,ACC}(\Delta s) = \pm 0{,}62$Ncm in Figure 11 (b).

Thus far, the calculations however exclude simultaneously occurring variation of different interfaces. In combination with a diameter tolerance of the pin (Comm. $\pm 0{,}12\ mm$), the third scenario therefore emphasises the possibility of tilting components, see Figure 11 (c). In addition to the varying spring deflection, it consequently implies a changing notch angle, hence a maximum loss of torque, which is given by the vertical displacement $\Delta s = \pm 0{,}18\ mm$ and the resulting angle change $\Delta\theta = -1°$. Based on the assumptions about the ingoing variation, the influence of only two interfaces can consequently be estimated to $\Delta\hat{T}_{ON,ACC}(\Delta s, \Delta\theta) = -2{,}13\ Ncm$.

4.2.4. Verification

By comparing two dimensions taken from the original design records (Hearing 2014d) with measurements from switch samples, the second verification step seeks to verify two assumptions made throughout this contribution, i. e. whether:

(1) the variation of the physical assemblies is roughly reflected by the tolerance estimations made in section 4.2.1.
(2) the effects of poor interfaces clarity can be seen in the difference between the component and assembly dimensions.

For the ten available service replacement parts, the height of one single component, i. e. of the lower housing h_1, and the overall height of the assembled device h_2 were taken with a calliper, see Figure 12 (a). First of all, the measurements of single components illustrate that the values for *commercial tolerances*, given in SPI (1998) and used in section 4.2.1, might overestimate the actual dimensional variation. In case the outliers are disregarded, no. 1, 3 and 4 in Figure 12 (c), the measured height of the lower housing shell lies in a range of $h_1 \in [16{,}24\text{ mm};\ 16{,}28\text{ mm}]$, and thus even falls below the tolerance value for *fine tolerances* $\Delta\hat{h}_1 = \pm 0{,}065$ mm.

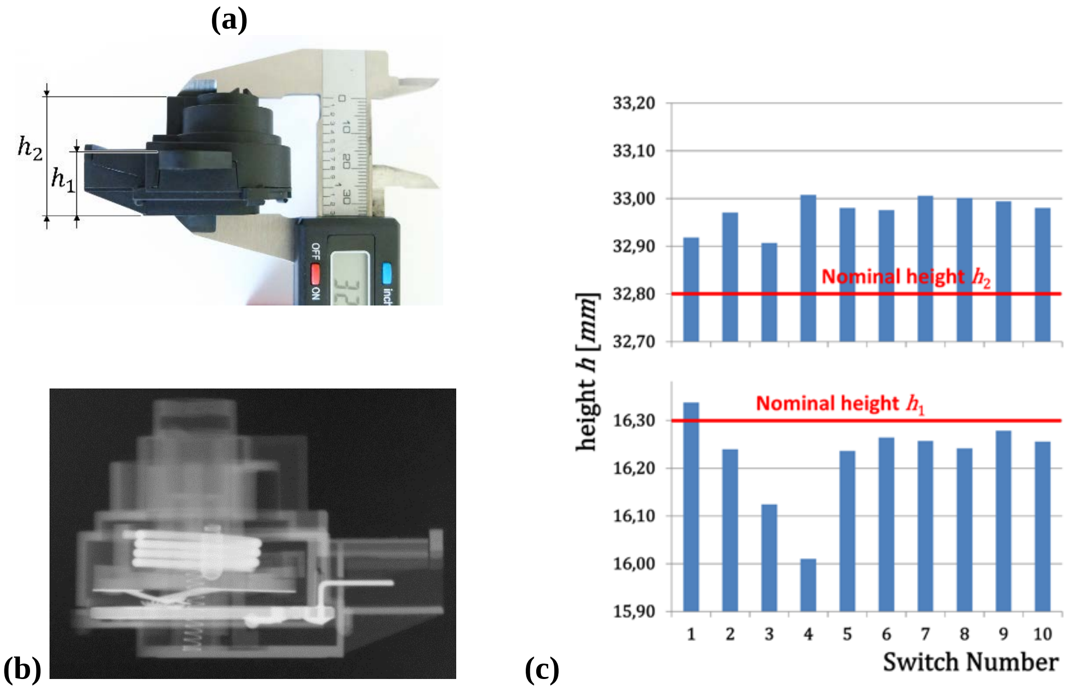
(a) (b) (c)

Figure 12. Verification of results based on (a) manual measurements, (b) optical measurements, adopted from Hearing (2014a), and (c) the comparison component or device dimensions to specified nominal values**.**

Despite this inaccurate estimation, a comparison with the measurements of assembled devices suggests that a lack of interface clarity is one contributor to the switch's varying performance. While the dimensions of single components are likely to be under their specification level, the measured height of the assembled device persistently exceeds the specified nominal value, see h_2 in Figure 12 (c). As approximated by the analyses in section 4.2, ambiguous interfaces and unpredictable mating conditions between components appear to have a effect on the distance between the housing shells, and thus on the spring deflection Δs as well as the torque level $T_{ON,ACC}$.as also illustrated in Figure 12 (b).

5. Discussion

The case of the GM ignition switch recall offers a unique possibility to create awareness of the relevance of early stage robust design efforts as well as of a systematic analysis of variation during product development. It has been shown thus far, that rather simple RD methods can be used to predict factors, which contribute to the switch's performance variation. At the same time, it has to be noted though, that the analysis exclusively focusses on variation within the switch. To understand the full picture related to performance variation, this section will therefore move the focus to external influences, to a discussion of the taken mitigation actions, as well as of the challenges of a coherent robustness analysis.

5.1. External variation influences

The analysis within this paper focusses exclusively on variation of DPs, thus variation influences, which are subject to company-internal control mechanisms. For a comprehensive consideration of the product's robustness, unforeseen noise factors or potential variation of use patterns also need to be factored into the analysis but are even more challenging to predict. An example of external noise factors is the varying weight of the key chain, which can be further amplified by varying degrees of road undulations. In addition, the Valukas (2014) report also identified varying user interactions as an additional root cause for the malfunction of switches. Depending on the seating position, it was deemed possible for the driver's knee to come into contact with the key.

5.2. Mitigation actions

The conducted analysis also reveals the mitigation actions taken by GM and the supplier Delphi, which are at least debatable from a RD perspective. Although aware of inconsistently and underperforming ignition switches, no efforts measures for a systematic assessment and avoidance of underlying variation-effects is documented. Instead, the resposnible engineerings seem to have exclusively focused on "*short-term containment*" solutions (Valukas 2014, p. 68), include the increase of spring length described in section 2.3, or the use of the key insert plug shown in Figure 13 (a), which aims at a reduced torque that the key chain can transmit to the ignition switch (Hearing 2014e, Valukas 2014).

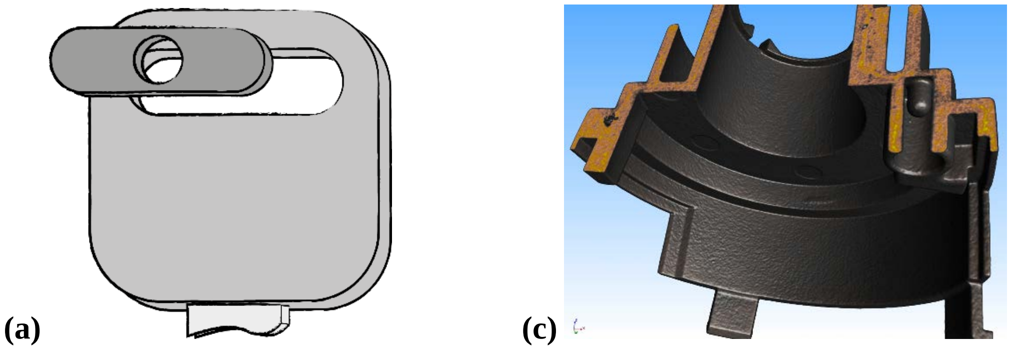

Figure 13. Containment solutions: (a) key insert plug and (b) CT Scan illustrating the effects of a reduced spring diameter

An additional example revealed in the process of this research is illustrated in Figure 13 (b). In a CT scan of the upper housing shell, a protrusion at the base of the spring hole was discovered. Originally an assembly feature to hold the spring in place, this protrusion was opportunistically used to create a greater spring compression by reducing the spring diameter from $0{,}75\ mm$ to $0{,}7\ mm$ in order to ensure that the spring would mate on top of the protrusion rather than around it. From a RD perspective, this measure is however likely to entail an even larger variation risk due to ambiguous contact surfaces between assembly feature and spring. Particular worrying from a RD perspective, the exclusive focus on an increased spring force will in general implicate greater stresses and deformations in the switch’s components, and thus potentially lead to effects, such as the angled switch plate described in section 4.2.3. At the same time, an increase of the spring force also disregard the existence of an upper specification limit, i.e. the fact that the customer will be experiencing quality loss when they feel that the key is too difficult to turn. By simply shifting the torque to a high level in order to mitigate variation instead of dealing with the variation, quality is sacrificed.

Ultimately, the authors would therefore like to underline, that all “quick and dirty” containment solutions, should always be carefully evaluated from a RD perspective and (although sometimes unavoidable) certainly do not replace an in-depth analysis and understanding of variation root causes.

5.3. Further research on Robust Design

Besides fostering awareness for the relevance of variation-effects, the analysis furthermore offers a unique possibility to illustrate some essential challenges of a coherent RD-driven analysis. Exemplary questions for ongoing research are a more data-driven identification of unexpected failure modes (Kemmler et al. 2015, section 4.1.1), the applicability of sensitivity and/or robustness indicators (Göhler et al. 2016a, section 4.1.3), a more systematic use of manufacturing variation data and corresponding standards for design purposes (Eifler et al. 2016, section 4.2), as well as the development of a coherent robust design process to align available RD tools and methods (Göhler et al. 2016b).

6. Conclusion

This contribution presents a critical analysis of one of the most infamous product recalls in automotive history from a variation-focused RD perspective. The case study shows that the application of available RD methods and tools, such as sensitivity studies, tolerance analyses, or Design Clarity, allows for deeper insight into the switch’s functionality and the impact of variation. It consequently extends previous analyses, conducted in the course of federal investigations, which still largely ignored the fact that the switch had large variations in performance (indicating a lack of robustness) and instead still mostly focus on the analysis of the “nominal design”.

In conclusion, the contribution gives a valuable overview of the immense and frequently disregarded potential of systematic RD-efforts in early design stages as well as of actual and future challenges for a RD-implementation in industrial practice. In this way, the authors hope to have contributed to establish a deeper understanding of the relevance of variation-effects as well as a more variation-focused mindset among academics and practitioners, and to have stimulated future, essential research in RD.

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