Understanding “Death by GPS”: A Systematic Study of Catastrophic Incidents Associated with Personal Navigation Technologies

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ABSTRACT
Catastrophic incidents associated with GPS devices and other personal navigation technologies are sufficiently common that these incidents have been given a colloquial nickname: “Death by GPS”. While there is a significant body of work on the use of personal navigation technologies in everyday scenarios, no research has examined these technologies' roles in catastrophic incidents. In this paper, we seek to address this gap in the literature. Borrowing techniques from public health research and communication studies, we construct a corpus of 158 detailed news reports of unique catastrophic incidents associated with personal navigation technologies. We then identify key themes in these incidents and the roles that navigation technologies played in them, e.g. missing road characteristics data contributed to over 24% of these incidents. With the goal of reducing casualties associated with personal navigation technologies, we outline implications for design and research that emerge from our results, e.g. advancing “space usage rule” mapping, incorporating weather information in routing, and improving visual and audio instructions in complex situations.

Author Keywords
GPS; SatNav; personal navigation technologies; map apps

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

INTRODUCTION

A tourist drives his rental car across a beach and directly into the Atlantic Ocean [16]. A person in Belgium intending to drive to a nearby train station ends up in Croatia [46]. A family traveling on a dirt road gets stranded for four days in the Australian outback [45]. These incidents all have one major factor in common: playing a key role in each incident was a personal navigation technology, i.e. a GPS device, a mobile map app (e.g. Google Maps, Apple Maps) or a “SatNav”.

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Catastrophic incidents associated with personal navigation technologies are sufficiently common that they have come to be associated with a colloquial name: “Death by GPS” [34]. While thankfully not all of these incidents involve the loss of life, it is not uncommon to see media reports of people endangering themselves or others and/or causing extensive property damage due in part to their interaction with a personal navigation technology.

It is tempting to blame these incidents on users and users alone. Indeed, reports of these incidents are often peppered with comments from witnesses and observers inquiring as to why drivers “wouldn't question driving into a puddle that doesn't seem to end” [34] and did not notice “multiple-language traffic signs” [46]. However, it is our responsibility as HCI researchers to design better systems that help people avoid making “user errors” [36], especially when these errors involve such extensive human and financial costs.

The geographic human-computer interaction (“GeoHCI”) [17] literature includes a relatively large body of work that examines how people use GPS-based navigation technologies in standard scenarios and in the course of their everyday lives (e.g. [7,18,21,27,28]). However, no work has focused on the increasingly large number of catastrophic incidents associated with these technologies. In other words, the “Death by GPS” phenomenon has yet to be studied in a rigorous fashion.

This paper seeks to begin the process of addressing this gap in the literature. As has been pointed out in the work on typical interactions with GPS devices [7], a major obstacle to the systematic analysis of “Death by GPS” incidents is that no database of these incidents exists. Additionally, methods that have been used to study interaction with GPS devices in the past (e.g. lab studies, field studies) are not valid for this type of analysis.

To overcome these obstacles, we turned to an unlikely source of data: news articles. This approach is adapted from the public health literature, where news articles are used as sensors when the research topic is of sufficient significance but no authoritative dataset is available. Using rigorous best practices for building a minimally biased-corpus of news stories and expert-led qualitative coding, we collected and analyzed a dataset of 158 news stories about unique catastrophic incidents associated with personal navigation technologies.

In our analyses of this corpus, we had two cascading research goals:

Goal 1: Identify the *patterns* that characterize catastrophic incidents associated with personal navigation technologies.

Goal 2: Use the identified patterns to generate *implications for research and design* that can help *build safer personal navigation technologies*.

More specifically, for our first goal, we sought to ascertain themes in both the basic properties of these incidents (e.g. Who was involved? What happened?) and themes in the roles that navigation technologies played in the incidents (i.e. How did the navigation technology specifically fail the user?). Based on the identified patterns, our second research goal involved outlining a series of concrete steps that researchers and practitioners can take to prevent the reoccurrence of common types of catastrophic incidents (and save lives).

We find, for instance, that a large number of "Death by GPS" incidents are single-vehicle collisions (likely far more than accidents caused by other factors), that stranding events were the next most common type of incident, and that distraction by a navigation device was significantly associated with more serious incidents. With regard to the roles of technology, we observed that missing road characteristics attributes (e.g. road surface types and current condition) had a substantial effect, as did the failure to correctly infer routing preferences (among a series of other factors).

The implications for research and design that emerge from our findings span the spectrum of "GeoHCI" topical domains. For example, we discuss how our results highlight the importance of (1) incorporating vehicle type and weather information into routing algorithms, (2) improving navigation guidance in the face of complex geographies, and (3) developing separate interfaces for tourists and locals. More generally, our results show that navigation devices can be more intelligent about safety than their current state-of-the-art: telling users to pay attention to their environment when the device is turned on. Blanket warnings like these are known to be ineffective in HCI [35], and our results show a path forward towards improved approaches.

In summary, this paper makes the following contributions:

1. We perform the first research that systematically characterizes catastrophic incidents associated with personal navigation technologies and the role that these technologies played in these incidents. We identify major themes in the incidents themselves and in the roles played by technology.
2. With the goal of preventing the patterns we identified in these catastrophic incidents from reoccurring, we outline a series of implications for research and design that can help us develop safer personal navigation technologies.

To further research on this topic, we are also releasing the core dataset we developed for this paper[1]. This dataset consists of the complete corpus of 158 news stories along with all the codes we applied to each story in the process described below. To make our findings more accessible, we are also releasing an interactive web map version of the corpus, which allows users to see the approximate location of each incident and further information about the incident[2].

A Note on Terminology: The subject of this research resulted in several terminological challenges. The core technologies of interest to this paper – GPS devices, SatNav devices, and mobile map applications like Google Maps and Apple Maps – are often referred to using the term "GPS". This term ignores the diverse positioning techniques (e.g. Wi-Fi positioning), routing algorithms, and cartography built into these technologies, so we felt it was imprecise to use this more casual language given the nature of this paper. As such, we use the term "personal navigation technology" (sometimes shortened to "navigation technology" or "navigation device"). Similarly, given the diversity of the types of incidents in our corpus, assigning this class of incidents a formal name was not straightforward. We chose the term "catastrophic incidents" in accordance with the "extremely unfortunate or unsuccessful" definition of "catastrophic" [50].

RELATED WORK

This work's core motivation primarily emerges from two areas in the "GeoHCI" literature: (1) work that has examined the use of personal navigation technologies in standard scenarios and (2) research that has looked at the long-term behavioral and cognitive effects of using these technologies.

Navigation Technologies in Standard Scenarios

Researchers began to investigate HCI issues associated with in-car navigation systems almost as soon as these technologies were first commercialized [10,11,48]. This thread of research covers a diverse set of topics including attention demands [11,23,48], cartography [27,33,42], different modes of output [9,21] and age-related variation [2], all with a focus on *everyday usage scenarios*. For instance, Kun et al. [23] conducted a lab simulation study and found that graphical GPS interfaces distracted users from the primary task of driving. Medenica et al. [33] coupled augmented reality with in-car GPS navigators and showed that this combination reduced drivers' distractions. Jensen et

[1] The dataset can be downloaded here: https://goo.gl/8vE14V

[2] The interactive map is available here: https://goo.gl/jlQ8S4

al. [21] compared different interaction modes of in-car GPS navigators and concluded that the combination of audio-visual output is preferred by drivers, but did not significantly reduce device-related distractions.

The projects in this research thread that most directly motivated our work are those of Hipp et al. [18] and Brown and Laurier [6]. Both studies considered the "troubles" drivers encountered with in-car GPS devices in typical driving situations. Hipp et al. [18] conducted a traditional user interface evaluation to compare the performances of different types of in-car navigation systems on the same route. They identified unexpressed routing preferences, failure to understand intentional detours from planned routes, and the lack of real-time traffic information as the common interaction weakness of commercial navigators (with the latter now being fixed in most modern navigation technologies). Brown and Laurier [7] carried out an interaction analysis in which they observed and interviewed drivers about their daily uses of in-car GPS to understand their navigation practices. They outlined five types of "normal troubles" of using in-car GPS navigators in everyday driving: destination, routing, maps and sensors, timing of instructions and inflexibility of the technology.

This work is distinguished from that above in that instead of studying the use of personal navigation technologies in standard scenarios, we focus on catastrophic incidents that involved these technologies. Some of the roles that these technologies play in catastrophic incidents are similar to those identified in the literature on standard scenarios, and other roles are new to the literature (as are the resulting design implications). We discuss the relationship between our findings and the findings from prior work in detail below.

Long-term Impact of Navigation Technology Use

Another class of relevant research focuses on understanding the behavioral and cognitive changes produced by personal navigation technologies. For instance, Leshed et al. [28] conducted an ethnography-based study and showed that drivers using GPS-based navigation technologies are disengaged from their surrounding environment. Aporta and Higgs [3] examined the long-term impact of navigation technology at a larger scale, arguing that the adoption of navigation technologies has alienated many Inuit hunters from the traditional wayfinding skills they have depended on for thousands of years. Other studies have looked at the cognitive impact of navigation systems. For instance, Gardony et la. [13] conducted a lab-based simulation study and demonstrated that these devices may impair users' ability to record information about the environment and their spatial orientation. The findings of this line of work inform this paper's research and design implications, specifically those related to the multifaceted relationships between a navigation technology, its user, and the environment.

METHODS

Although catastrophic incidents associated with personal navigation technologies are sufficiently noteworthy to have been given a moniker – "Death by GPS" – no authoritative dataset of these incidents exists. The high stakes of these incidents make them worthy of study, but the lack of available data and relative rarity of these incidents make it difficult to analyze them. Additionally, lab experiments or other simulations are not currently well-suited to this research area.

Fortunately, the domain of public health has significant experience studying phenomena with the same core properties as "Death by GPS" incidents, i.e. relatively rare phenomena of media interest for which no authoritative dataset is available and for which simulations are not currently tractable. Specifically, to examine these phenomena, researchers in this domain have followed a two-step pipeline: (1) build a corpus of news stories describing these incidents and (2) analyze the corpus using expert-led qualitative coding techniques. For example, in the absence of a national surveillance system for homicide-suicide in the United States, Malphurs and Cohen [31] collected and coded related news articles from 191 national newspapers to identify the number and subtypes of such incidents. This approach of relying on newspapers to summarize the characteristics of homicide-suicide incidents has also been applied in the Netherlands [29] and Italy [40]. Similarly, to study the collisions between wheelchairs and motor vehicles, a type of accident that is not distinguished in police reports, LaBan and Nabity [24] gathered 107 news articles using LexisNexis. They analyzed this corpus to understand gender incidence ratios, proportion of different types of motor vehicles, the time of incidents, and other characteristics of these incidents.

In this paper, we adopt this approach from the public health literature. To do so, we first verified that no relevant authoritative dataset exists by contacting several local police departments and national agencies, including the Minneapolis Police Department (USA), the Aachen Police Department (Germany), National Transportation Safety Board (USA) and National Highway Traffic Safety Administration (USA). We then implemented the pipeline from public health, using the process described in more detail below.

Phase 1: Corpus Development

One of the key challenges in the public health-based approach is gathering the corpus of news articles. Most prior work has relied on one of two methods: (1) an exhaustive search in the local newspaper of a specific study site (e.g. [5,38]) or (2) unstructured but extensive querying of news search engines (e.g. [24,31]). Since our work is not well-suited to a specific study site, we implemented a more robust version of the latter approach using best practices from communication studies for sampling news stories with minimal bias [25,44].

The first step in this minimal bias sampling approach involves leveraging prior research in this space (i.e. the literature covered in the Related Work section) to seed a set of keywords, which is then grown using a variety of structured strategies (e.g. synonym generation). These keywords are then used to iteratively query a news database (in our case LexisNexis), with the set of keywords refined at each step. Achieving acceptable precision for one's keywords is particularly important given that these databases often have strict limits on the total number of news stories that can be returned for a given query (e.g. LexisNexis's is set to 1000 stories). We were able to achieve a precision of 40.8%, which is within acceptable parameters [44]. This left us with 408 articles that were related to catastrophic incidents associated with personal navigation technologies. We note that we restricted our search to stories published in 2010 or later to ensure that our findings are relevant to modern personal navigation technologies (e.g. smartphone map apps) rather than early-generation devices. Additionally, due to language constraints with respect to the database and the coders, we only searched for stories written in English, a subject we cover in more detail in the limitation section.

Two challenges remained before we could begin the next stage of the pipeline. First, many of the articles were opinion columns about the "Death by GPS" phenomenon and did not describe specific incidents. Second, some incidents were described by two different journalists in two different publications. To remove these articles from our dataset, two researchers conducted an exhaustive search, reading each article and evaluating its validity for our study and matching duplicates (we kept the more detailed of any two stories on the same incident; disagreements were resolved through discussion).

In the end, we were left with a corpus that contains 158 news stories, each describing a unique catastrophic incident associated with personal navigation technologies. For replication purposes and for researchers who may want to apply this method in other contexts, we have included additional detail about how we implemented our corpus-building procedure in the documentation of our coded dataset. We also discuss the one minor change we had to make to the standard procedure to adapt it to the goals of our research project: we could not simply use the keywords from prior research on interaction with navigation technologies because these only focused on standard scenarios. As such, we used a slightly more iterative keyword generation method in which researchers identified keywords from small samples of actual relevant news stories.

Phase 2: Expert-led Coding

The second stage of the public health pipeline involves employing a relatively standard qualitative coding procedure with an important exception: coders are domain experts. This expertise enables coders to map properties of incidents reported in news articles to pre-existing topics in the literature of interest, or to new challenges when relevant. In our case, our two coders (members of our research team) had extensive expertise in both geography and HCI, the two fields most associated with our research questions. More specifically, each coder had both a Masters' degree in geography or geoinformatics and a Masters' degree in computer science (with a focus on HCI).

The specifics of the coding process were as follows: using a small seed corpus, knowledge of our research goals, and expertise in the research domain, our coders jointly established a series of coding dimensions. Next, using a random sample of 10 articles, the coders jointly developed a list of codes for each dimension and developed a corresponding codebook (this is included in our dataset). Both coders then evaluated a set of 40 overlapping articles to assess each dimension for interrater reliability. Importantly, when it was not possible to assess an article for a particular coding dimension, coders left the value blank.

The Cohen's Kappa of coders' results on all dimensions ranged from 0.69 to 0.95, which indicates "substantial agreement" [26]. Of particular note, we achieved a Cohen's Kappa of 0.79 for the *Technological Cause* dimension, which is the basis for a set of key findings below. As the Cohen's Kappa was sufficiently high for all dimensions, coders evaluated the remaining articles on an individual basis.

Beyond *Technological Cause*, other major coding dimensions that were considered included the *Seriousness* of the incident (e.g. Was death involved?), the *Incident Type* (e.g. Was it a single-vehicle collision? Did a vehicle get stranded?), *Weather*, *Road Surface* (e.g. Was it on a dirt road or a paved road?), whether *Distraction* was explicitly noted as an issue in the article and whether the driver was a *Local Driver* or Non-local Driver to the area of the incident. A complete list of dimensions and their corresponding specific codes is included in our public dataset. For the major coding dimensions, coders were able to assign codes for over 90% of incidents with the exception of *Local Driver*, in which 37% of incidents could not be coded.

Interpretation of Results

As described above, there is a consensus (e.g. [22,24,29,31,38,40]) in the public health literature that when no authoritative data is available, the news article-based pipeline we employ here can provide valuable early insight about a phenomenon of interest. However, news article-derived data has its share of limitations, as is the case with many datasets considered in public health (e.g. even authoritative crime datasets have been criticized for potentially strong racial biases [39], an issue the computing community has been facing in association with predictive policing technologies [20]). To the best of our knowledge, our use of news article-derived data is novel to the HCI literature. As such, we believe that highlighting the known limitations of this type of data early in the paper is important so that our results can be interpreted in proper context.

The most significant limitation of news article-derived data is a risk of "newsworthiness" bias, or an overrepresentation of incidents that are in alignment with the incentive structures of news organizations. While at least one study has found no such bias (e.g. [38]), others have found newsworthiness bias to manifest as an overrepresentation of (1) accidental incidents (e.g. fewer suicides, more unusual events) or (2) more fatal incidents (e.g. more murders, fewer assaults) [12]. All incidents that we examine are accidental in nature, making the accidental bias less relevant [12,38]. However, a potential bias towards fatal incidents is important to consider when examining our results below.

To minimize further risk of bias, we employ robust statistical tests when making comparisons between types of incidents. In most cases, we are able to simply use Pearson's Chi-squared test of independence. However, in circumstances where the assumptions of Chi-squared distribution are violated due to relatively small sample size, we used a likelihood ratio G test of independence, a best practice suggested by [1,32]. All *p*-values reported in the paper have been subject to Bonferroni correction.

Newsworthiness bias mainly affects proportional results (i.e. comparisons between incident types), which are a small percentage of the results we present below. The bulk of our results are either qualitative descriptions of incidents or absolute values (e.g. raw counts of incidents of certain types). Our absolute results should be interpreted in the context of a limited understanding of the size of the incident population, i.e. we do not know what share of catastrophic incidents associated with personal navigation technologies are included in our news corpus. However, even if the incidents in our sample are close to the entire population, the aggregate devastation to blood and treasure of just these incidents make them worthy of analysis and discussion in the HCI literature, which does not often examine such high-cost interactions with technology. In order to add additional context and further this discussion, we provide qualitative descriptions of incidents wherever space allows.

RESULTS

In this section, we provide an overview of the major results that emerged from our coding process. In doing so, we seek to address our first research goal: characterizing patterns in catastrophic incidents associated with personal navigation technologies. We organize our thematic findings into two groups (1) themes in the basic properties of these incidents and (2) themes in the technological causes of these incidents. We discuss each group of findings in turn below.

Basic Properties

Many People Have Died in Incidents Associated with Personal Navigation Technologies

Table 1 shows the results of our coding for the *Seriousness* of the incidents with respect to human and financial cost. Clear in Table 1 is that navigation technologies have been associated with some truly tragic events: our corpus describes the deaths of 52 people in total, including two children. These deaths occurred across 45 incidents, or 28% of our corpus. Additionally, our corpus contains 23 incidents (15%) that resulted in significant bodily harm, but not death.

Seriousness of Incidents	#	%
Major (deaths)	44	28%
Major (injuries)	23	15%
Medium (e.g. property damage, legal consequences)	52	33%
Low (e.g. significant inconvenience)	39	25%

Table 1. Distribution of the *Seriousness* of incidents.

Although the proportion of fatal incidents in our corpus may be exaggerated due to the aforementioned newsworthiness bias, the absolute number of deaths (and injuries) associated with navigation technologies that we have identified is alarming. GPS devices, mobile maps, and other navigation technologies provide us with tremendous benefits, but these results indicate that they also have a set of costs that had not yet been systematically enumerated. These results also highlight the importance of better understanding catastrophic incidents like those studied here, as well as using this understanding to design safer technologies.

Table 1 also shows that "Death by GPS" is not the ideal term to describe incidents associated with navigation technologies that have serious implications. Over 50% of the incidents in our corpus did not involve death or significant injury, with the damage in these cases being primarily of a financial or other nature. Examples of these incidents include a group of skiers who intended to go to La Plagne, a famous ski resort in the Alps, but ended up arriving at Plagne, a town in southern France that is 715 km away (article #46[3]). Another example involved five men who drove onto a nuclear power plant's property at the behest of their navigation device and were suspected of terrorism (article #95).

The Most Common Incident Type is a Single-Vehicle Crash, but There is Substantial Incident Type Diversity

Table 2 depicts the results of our coding for *Incident Type* and shows that the most common type of incident in our corpus is car crashes. However, the table also shows that crashes are far from the only type of incident we encountered. For instance, almost 20% of incidents resulted in cars being stranded in very rural areas and over 15% involved people going on substantial detours. We were also surprised by the number of reports (7) of people driving on the wrong side of the road for an extended distance. Such examples include a person who drove 48km on the wrong side of a highway after following her device's instructions to enter the wrong freeway ramp (article #90) and a 37-year-old man who was caught driving the wrong way on an Australian

[3] News article numbers refer to the index in our released dataset.

Types of Incidents	# (%)
Trespass (violate space usage rules)	5 (3%)
Wrong way (opposite side)	7 (4%)
Detour (e.g. wrong address)	25 (16%)
Stranded/stuck (e.g. in the wildness, on railroad tracks)	31 (20%)
Crashes	90 (57%)
Crashes with pedestrians/bikes	13 (8%)
Crashes with vehicles	26 (17%)
Single-vehicle collisions	51 (32%)

Table 2. Distribution of *Incident Types.*

highway for more than 10 km and attributed the error to his navigation device (article #12).

In Table 2, we also show subtypes of the Crashes incident type. We found that single-vehicle collisions comprised the majority of crashes (51 cases, 32% of overall incidents), with crashes with other vehicles (26 cases, 17%) and crashes with pedestrians and bikes (13 cases, 8%) making up the remainder of crash incidents. To understand single-vehicle collisions in more detail, we did an additional round of coding to identify more detailed themes (this was done by a single expert coder). Here we found that vehicles colliding with buildings, walls, and guardrails due to excessively narrow roads were the most common type of single-vehicle incident. Crashing with low overhead bridges is another common occurrence in our corpus, with a diverse array of other objects in the environment being the subject of the remainder of the single-car crashes.

Personal Navigation Technology-related Crashes Appear to Be Proportionally Different Than Typical Crashes

To put the above results in context, we utilized The National Automotive Sampling System General Estimates System (NASS GES) dataset from the U.S. National Highway Traffic Safety Administration [49]. The NASS GES dataset contains a representative sample of vehicle crashes of all types as reported by police. While not directly comparable to our corpus, the NASS GES can provide a sense of whether personal navigation technology-related crashes are distributionally similar to the population of car crashes, or whether the role played by navigation technology manifests in different types of crash outcomes.

Our results suggest that the latter is the case: crashes associated with personal navigation technologies appear to be different in type relative to typical crashes. For instance, only 15% of car crashes in the NASS GES dataset are single-vehicle collisions, whereas the same type accounts for 57% of crashes in our corpus (Table 2). Moreover, crashes associated with building/walls/guardrails and overhead bridges are much less common in the NASS GES dataset, comprising less than 2% of crashes overall, while in our corpus they account for 42% of all crashes. Among other implications, this result provides further evidence that simply adopting standard recommendations from traditional traffic safety research will not be able to address the safety concerns associated with personal navigation technologies.

Unfamiliarity with One's Surroundings Plays a Key Role

A substantial percentage of the incidents in our corpus occurred when users of personal navigation technologies were outside of their home region. Specifically, 78% percent of the incidents involved non-locals and only 22% percent involved locals. Some examples of incidents involving non-locals include one story in which a person drove her car into a swamp (article #23). The driver was quoted as saying "This was the road it told me to take … I don't know the area at all, so I just thought it was okay". Another incident consisted of a driver hitting and killing a pedestrian, with the corresponding news article reporting that "the driver was unfamiliar with the area and was adjusting her GPS navigational system" (article #71).

While the use of navigation technologies likely increases outside of one's home region, this result does suggest that user interfaces for navigation technologies may want to encourage more caution and support users in different ways when they are in their home region and when they are traveling. We discuss these implications for design in more detail below.

Distraction Leads to More Serious Incidents

We identified a significant association between our *Distraction* coding dimension and our *Seriousness* dimension, with distraction leading to many deadly incidents ($\chi^2(2) = 19.2,\ p < .05$). Examining the 21 deadly incidents that involved distraction in more detail, we found that in five cases, people were using non-critical features of their navigation device. For instance, a driver killed a cyclist while "using the zoom-in function" (article #33) and another driver from Springfield injured a bicyclist while "looking for place to eat on GPS" (article #40).

Stranding Risk Increases with Dirt Roads, Bad Weather, and Especially Both at the Same Time

We observed significant associations between our *Road Surface* coding dimension and our *Incident Type* dimension. In particular, if vehicles were traveling on a dirt road, there were more than the expected number of stranding incidents ($G^2(12) = 53.0,\ p < .05$). This was especially the case when weather was a factor. Examples include a medical student from Quebec who followed GPS and got stranded on a logging road for three days in the snow (article #4) and a British couple and their children who were stranded for four days on an unsealed road that was made muddy by torrential rain (article #115). Interestingly, the latter family thought that their in-car GPS device was suggesting a significant shortcut and followed its instructions as a result, a point we return to later.

More generally, we found significant interaction between disaster type dimension and the weather dimension ($G^2(4) = 21.1,\ p < .05$). Specifically, there are more than the expected

Technological Causes	# (%)
Missing or incorrect geographic objects	5 (4%)
Geocoding (i.e. associating toponym and its coordinates)	7 (6%)
Incorrect toponym disambiguation (i.e. select similar but wrong destination)	8 (7%)
Instructions/visualization	18 (16%)
Non-transparent/wrong route preference	18 (16%)
Missing or incorrect attributes	64 (53%)
Physical characteristics of the road (e.g. road surface, road widths)	30 (25%)
Clearance height	17 (14%)
Traffic rules (e.g. no left turn)	5 (4%)
Temporary blockage	3 (3%)
Geopolitical boundary (e.g. country border)	2 (2%)
Private area	2 (2%)
Ferry line as road	3 (3%)
Bridge limitation	2 (2%)

Table 3. Distribution of *Technological Cause*. Note: The # does not add up to 158 because coders did not enter a code when there was not enough information in given news story to make a certain type of assessment.

number of stranding incidents under severe weather, as one might anticipate.

Technological Causes

Table 3 shows the results of our coders assessing each article for its *Technological Cause*. In this section, we discuss the themes in the distribution of these results, as well as the findings from a more detailed coding that we conducted to understand important trends.

Attributes that are Missing or Incorrect Are a Major Problem

Geographic information, like that which is used in routing for personal navigation technologies, consists of two components: spatial information and attributes of that spatial information [14]. Broadly speaking, in a routing context, the spatial information is the location of a road and the attributes consist of key properties of the road (e.g. the speed limit).

Our results in Table 3 suggest that missing and incorrect attributes play a major role in the catastrophic incidents in our corpus, being in part responsible for 64 (53%) of these incidents. To better understand the types of attributes involved, one expert conducted a second round of coding to determine the types of attributes that were most often missing or incorrect and the results are also included in Table 3. The physical characteristics of the road (e.g. width, surface) (30 incidents) and clearance height (17 incidents) were by far the most common type of attributes that were missing or incorrect. Indeed, stories about routing algorithms neglecting the road characteristics and the heights of overpasses are pervasive in our corpus. For example, as noted above, failure to incorporate road surface information led multiple sedans to be stranded on unpaved roads (often in a very dangerous fashion) (e.g. article #4, #115) and multiple trucks ran into serious trouble due to low-clearance roads (e.g. article #6, #34, #36). Indeed, we found trucks were more susceptible to suffer from attribute related issues due to this problem as evidenced by the significant interaction between our *Vehicle Type* coding dimension and the *Technological Cause* dimension ($G^2(15) = 67.4$, $p < .05$).

Another theme present in the attribute types in Table 3 is the notion of "space usage rules" (SURs) [41], or regulations associated with the use of a certain area (in this case, a road). For instance, in one incident, a truck that traveled on truck-prohibited road killed a father and a daughter in a sedan (article #27). In another, an in-car GPS device guided a driver up a private driveway, and the driver ended up in a physical confrontation with the owners of the property (article #102).

Cartographic and Audio Instructions Are Not Capable of Handling Complex Geographic Contexts

Table 3 shows that almost 18 incidents involved an issue with routing guidance, either in visual (cartographic) or audio form. Past work on the use of GPS devices in standard scenarios identified that excessive instructions are a significant problem with GPS usability [2,7]. While we did observe this problem in our corpus, many of the incidents given this code by our experts related to a different issue: the inability of the personal navigation technology to help drivers navigate *complex geographic contexts*.

For example, in one story in our corpus, a person who was driving at night was faced with a freeway on-ramp that was immediately parallel to a railroad track (article #146). Figure 1 shows a Street View image of the exact location of the incident. When the driver's navigation device asked him to turn right, the driver turned onto the railroad tracks as the instructions were ambiguous. Ten kilometers later, the driver's car was destroyed by an oncoming train, but fortunately the driver survived by jumping out of the car. Similarly, article #66 tells a tragic story in which a bicyclist was hit by a driver who ignored a "Yield" sign at a non-typical intersection because the driver's navigation device screen simply instructed her to "go straight". Wrong-way driving was particularly (and significantly; $G^2(24) = 100.1$, $p < .05$) associated with cartographic and navigation instruction issues, and complex geographies were common in these cases. For instance, one report in our corpus (article #39) describes the story of a driver who followed her navigation device's instructions to "take the first left turn" at a roundabout. However, the actual first left turn (not the first *legal* left turn) was the exit ramp of a freeway, and the driver – who was on the road at night – entered the freeway driving in the wrong direction. This driver sadly lost her life.

Standard Scenarios versus Catastrophic Incidents

As noted above, past work has done a rigorous job of identifying and categorizing problems encountered by users

Figure 1. A Google Street View image depicting the complex geography of the location of the incident in article #146.

of personal navigation technologies in standard usage scenarios. While the issues discussed above have not been highlighted in prior work, one additional contribution of the results in Table 3 is to add gravity to many of the previously-identified issues. For instance, in a study of challenges encountered in standard GPS device usage, Brown and Laurier [7] found that route preferences, out-of-date spatial data, the timing of navigation guidance, and positioning errors were key sources of user frustration. Some of these issues appear in Table 3, meaning that they were in part responsible for a number of catastrophic incidents in addition to more everyday usability issues.

Of particular note are Brown and Laurier's findings with respect to route preference. Route preference issues played a role in 18 (16%) of the news stories in our corpus, indicating they are a significant issue in catastrophic incidents as well as everyday usage scenarios. However, the route selection issues present in our corpus are of a substantially different character than those identified by Brown and Laurier. Specifically, while participants in Brown and Laurier's study wanted more route choice, people in our corpus were given too many choices (i.e. at least one was dangerous). For example, in one incident a Canadian couple got lost in rural Nevada after selecting the "shortest path" route option suggested by their navigation device, which included a little-maintained road. They were stranded in Nevada for 49 days, during which time the husband sadly lost his life (article #9). We return to this case and the issue of strict "shortest path" routing and route selection in the implications section.

With respect to prior work, it is also interesting to examine Table 3 for what is not common or present at all in our corpus. It appears that some issues with everyday use of navigation technologies do not play a role in catastrophic incidents associated with these technologies. For instance, positioning inaccuracies and the lack of adaptability to intentional "detours" were the sources of major usability challenges in the work of Brown and Laurier. However, neither appeared in our corpus. Similarly, missing spatial data was not a major issue in our corpus – it played a role in only 5 (4%) of incidents – but has been identified as a significant issue in standard usage scenarios. For catastrophic incidents, the issue appears to be attributes rather than the spatial data itself, a subject we discuss immediately below.

IMPLICATIONS FOR RESEARCH AND DESIGN

In this section, we turn our attention to our second research goal: helping to identify solutions to the problems we found in our results section by enumerating a series of implications for both research and design. Some of these implications suggest improvements to the design of existing systems, while other present important new challenges for the GeoHCI research community. We have organized these implications into two high-level categories corresponding to two broad areas of the GeoHCI research space: implications related to *spatial computing* (e.g. routing algorithms, missing attributes) and implications related *user interaction* issues.

Spatial Computing Implications

Geometries without Attributes Can Be Dangerous

A major finding above is that missing attributes play a substantial role in the catastrophic incidents in our corpus. This suggests that road network geometries may be "getting ahead" of the corresponding attributes. That is, data providers are adding road segments to their networks faster than they are adding the attributes to those segments that are necessary to facilitate safe routing.

These results suggest that data providers may not want to integrate road segments into their networks unless those segments have high-quality data for a core set of attributes. Based on our findings, these attributes should include the type of the road (e.g. dirt, asphalt) and the clearance height of the road (as defined by any overpasses, tunnels, and other obstacles) at minimum.

Incorporate Vehicle Type into Routing Decisions

Even when high-quality attributes are included, however, they must be used intelligently by routing algorithms. Returning to Table 3, a key theme emerges in this respect: many of the incidents included in this table could have been prevented if routing algorithms can understand the limitations of the vehicle that they are routing. For instance, it is often not safe for sedans to drive down rough country roads, and trucks should not drive down roads with low clearance heights. Coupled with good coverage of attributes, incorporating vehicle type information would be a straightforward and effective way to maintain good coverage of possible routes (e.g. allowing SUVs to drive down rough country roads), while at the same time increasing safety.

Extend Space Usage Rule Mapping Efforts to Road Networks

We identified that the lack of space usage rules (i.e. usage regulations) is a common missing attribute associated with the catastrophic incidents in our corpus. Space usage rules (SURs) have been a topic of growing interest in the GeoHCI research community in the past few years (e.g. [19,41,43]), but this literature has focused on mapping rules associated with regions rather than roads. For example, a common research challenge in SUR mapping is identifying regions in which smoking is legal or illegal [41].

Our research suggests that more effort should be spent on the identification of SURs for road networks. In particular, improving data related to the maximum clearance of roads, whether roads are public or private, and improved recognition of traffic rules are particularly important. Fortunately, unlike many SUR mapping challenges that require multifaceted approaches (e.g. natural language processing, crowdsourcing), it is likely that much of the work here can be done using computer vision (CV) approaches. The automated detection of traffic rules in this fashion is already underway [4]. It is likely that private property signs would present unique challenges for CV algorithms due to their diversity, but this is a contained problem that can likely be at least partially addressed with current state-of-the-art CV techniques.

The Weather Matters When Routing

Our results suggest that routing algorithms should consider weather information when generating routes, and should do so in concert with vehicle type information. A substantial number of the stranding incidents in our corpus would have been avoided with relatively straightforward weather- and vehicle-aware routing approaches. For instance, if it has rained 20 centimeters in the past day, routing algorithms should not send drivers of sedans down dirt roads. Similarly, if it has snowed 20 centimeters and it has stayed below freezing, routing algorithms should recommend that sedan drivers stick to main thoroughfares, which are plowed more quickly and more often (and should perhaps consider increasingly available information in many cities about which roads have been plowed since the last major snow).

The Downsides of Map Matching

We observed in our corpus that map matching techniques [15] can backfire. These techniques are designed to mitigate GPS noise by "snapping" vehicle locations to the closest road network geometry. However, they were likely involved in the three incidents in which a person drove on a train track parallel to a road (article #17, #32, #116) and also a few incidents in which people drove on the wrong side of the divided road (e.g. article #12, #90) (all cases happened in evening). In these cases, map matching algorithms likely "snapped" the driver's position to the nearest or the correct side of the road, making the driver believe that they were on right track (which may be difficult to assess at night).

Although more work is needed to understand this issue in detail, one potential improvement is to make map matching algorithms more error-sensitive in situations in which the distance between geometries is smaller than the error tolerance. Specifically, when an algorithm notices that there are multiple parallel linear geometries (e.g. a divided highway or a railroad parallel to a road), it can reduce the tolerance of its map matching radius. When observing a small, persistent mismatch for a short period, GPS devices could immediately prompt users about this mismatch and ask the driver to look at the environment to confirm that the vehicle is on a legal road.

User Interaction Implications

Route Preference Must Be Accompanied with Adequate Information to Make an Educated Choice

Past research on the use of navigation technology in standard scenarios has advocated for providing greater route preference for users. Our results suggest that this preference must be accompanied with adequate information for users to make safe decisions. Current navigation devices often offer multiple routing preferences such as "fastest", "shortest", or "eco mode". At the very least, these technologies should warn users that certain choice may involve traversing unsafe territory, as was the case with the Canadian couple that chose the "shortest path" through Nevada without understanding the consequences of doing so.

As mentioned above, in addition to the usability problem of excessive instructions with bad timing found by previous studies, we identified a new type of guidance-related problem: instructions that are too simple for the spatial decisions that the user has to make. Two research challenges emerge from this issue: (1) automatically detecting complex geographies and (2) developing interfaces to better support users in these contexts. With regard to the first challenge, public crash datasets (e.g. [49]) can provide ground truth information to help develop regression models that assess the complexity of a routing context based on the topology of the surrounding road network (and likely other information, such as railroads). The second challenge might be at least partially addressed through the use of image-based navigation, i.e. by annotating Street View imagery with arrows and labels. Image-based navigation is known to have benefits over most other approaches [47] but needs to be updated frequently to reflect any potential changes in the environment..

Local Mode and Non-Local Mode

Our results suggest that non-local drivers are at substantially greater risk for catastrophic incidents associated with navigation technologies than local drivers. These findings advocate for the development of customized features for each of these populations, i.e. a "local mode" and a "non-local mode". For instance, neuroscience research has shown that more attention is required when driving in an unfamiliar environment [30]. As such, designers should investigate strategies for reducing interaction with drivers when drivers are outside their home region(s). Additionally, routing algorithms could provide non-local drivers with an "easiest" route that prioritizes highways and avoids complex intersections to minimize the turn-by-turn instructions and general information load. Similarly, GPS devices could disable non-essential functionality (e.g. searching for local restaurants) while in unfamiliar territory and re-enable those functions only when drivers come to a complete stop (or return to their home areas).

DISCUSSION

In this paper, we provided the first characterization of the patterns in catastrophic incidents associated with the use of personal navigation technologies. We have also outlined a series of implications for design and research that emerge from these patterns. Below, we highlight several discussion points associated with this research.

First, it is interesting to reflect on the design implications in the context of automated vehicles. Some of the implications will clearly become moot if a human is not behind the wheel (e.g. those related to improved instructions), as will be the case for many of the core functionalities of navigation devices [6]. However, other implications may become significantly more important. For instance, adding attribute information to geometries, improving understanding of space usage rules and incorporating weather information will be critical to helping automated cars avoid dangerous navigation decisions. The same would likely apply in the nearer term with semi-automated cars, as recent work suggests that there may be excessive deference to automated routing approaches given the attentional challenges of partial automation [37]. Similarly, the research community has pointed out the need to keep drivers engaged when behind the wheel of a mostly-automated vehicle. Prompting users in the case of persistent map matching issues and engaging them in other difficult navigation-related tasks may be one way to accomplish this goal.

Second, the news article-based pipeline we use here may be able to help HCI researchers examine other difficult-to-study phenomena. As noted above, our public health-based approach is best suited to phenomena that share three properties: (1) no authoritative dataset is available, (2) instances are too rare to observe in large numbers in the wild and cannot be replicated in a lab setting, and (3) instances are frequently covered by journalists. Some additional HCI phenomena that share these properties include criminal events in the sharing economy and safety concerns related to location-based games like Pokémon GO [8]. To make it easier for researchers to employ our methodology, we have provided a step-by-step description of our approach in the documentation that is included with our coded dataset.

It is important to note that our coded dataset contains much more data than we could fully describe in this paper. While we have highlighted what we as researchers in the geographic HCI domain believe to be the most important themes in our results, other researchers may benefit from examining our data from a different perspective. One particularly interesting avenue of exploration that we are working to investigate is using the spatial locations of each incident (available in the dataset) to try to develop predictive models of the types of areas in which the use of navigation technologies might be particularly risky.

While we believe it is important for the HCI community to examine and learn from catastrophic incidents associated with the use of computing technologies, it is also important to put the relative incidence of these catastrophes in context. While we identified that GPS devices and related technologies played a role in at 158 catastrophic incidents involving 52 deaths, these technologies have also likely played a role in saving the lives of many people (e.g. guiding people to emergency resources, preventing people from getting lost). With this in mind, the design and research suggestions we make above are careful to be augmentative of existing navigation technology functionality rather than substantially altering current functionality.

Limitations

In addition to the drawbacks of the news article-based pipeline discussed above, this paper is also subject to several additional limitations. For instance, while our incident corpus is the first agglomeration of its type of any scale, future work should seek to increase this size by either finding more news stories or collecting data on incidents that are not reported in the news. With respect to identifying unreported incidents, crowdsourcing has been proven effective for building databases of technology failures in the domain of aviation [51]. This may be an approach that is feasible in this domain as well. Similarly, a related limitation of our dataset is that it that 97% of our articles came from either the U.S., the U.K., Canada, New Zealand, or Australia (due to the focus on English articles). It is reasonable to assume that patterns in other countries might be different, and future work should examine these patterns.

The issue of survivor bias should also be considered. It is likely that navigation technologies have played a role in a significant number of deadly accidents for which there was no witness or exogenous information to identify the role of the technology (the 44 deadly incidents considered here had one or both of these). Interestingly, survivor bias could counteract the fatality bias discussed above.

CONCLUSION

In this paper, we have extended prior work on user interaction with navigation technologies to consider catastrophic incidents associated with these technologies. We have characterized key patterns that exist in these incidents and enumerated implications for research and design that emerge from these patterns. This research increases our understanding of how the navigation technologies that we design cause serious harm, as well as provides a path towards developing safer navigation technologies.

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