Research vs. practice: An international review of challenges and opportunities in development and use of crash prediction models

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Abstract

Over the past ten years, crash prediction models (CPMs) have become the fundamental scientific tools of road safety management. However, there is a gap between state-of-the-art and state-of-the-practice, with the practical applications lagging behind scientific progress. This motivated the review of international experience with CPMs from the practitioner perspective: how and why should they consider using CPMs? Findings indicate that developing and using CPMs has its challenges. However, these may be minimised by increased communication between researchers (who develop CPMs) and agencies (who use CPMs), resulting in easy-to-use and transparent tools, which will also enable calibrating the CPMs to local conditions.

Introduction

Crash prediction models (CPMs) are mathematical equations, which link safety performance and risk factors. Over the past ten years, CPMs have become the fundamental scientific tools of quantitative road safety management, forming the foundation of the USA Highway Safety Manual (HSM) and the Australian National Risk Assessment Model (ANRAM). CPMs may be used for various key tasks, including network safety screening, economic analysis and road safety impact assessments. However, there are gaps between state-of-the-art (what is published by academics/researchers) and state-of-the-practice (what is needed/used by practitioners), which limits the practical use of CPMs. On this background, the presented review aims to investigate how are CPMs developed and applied. The answers should be of help to a user (e.g. an agency engineer/manager) asking about how and why they should consider using CPMs.

Methods

The goal of the review was to critically summarize international experience in the development and application of CPMs, with a focus on practical use by road agencies. In this regard, both scientific and practice-oriented literature was retrieved based on the following criteria:

- Sources:
  - academic: Web of Science and Scopus, including selected references (snowballing)
  - practical: reports of agencies (e.g. FHWA, Austroads, NZTA)
  - both: ARRB Knowledge Base, TRID database, reports of European institutes, EU project deliverables
- Keywords: accident prediction model, crash prediction model, safety performance function
- Language: English
- Time frame restriction: none

To focus on the typical road settings (the main road network, i.e. motorways/freeways/expressways and national roads), the following specific issues were not considered:

- Macro/planning-level applications (analysis based on land-use zones in assignment models)
- Specific CPMs for vulnerable road users, such as pedestrians or bicyclists
- CPMs for specific site elements (e.g. railway level crossings, bridges, tunnels, etc.)

The retrieved materials were mainly from Europe, Australia, New Zealand and North America. In order to stress the practical focus, the aim was to select the works related to the most frequent applications of CPMs.

The final literature selection thus focused on developing and using CPMs of typical elements (rural road segments or intersections), from the perspective of non-US practitioner, aiming to conduct typical tasks, such as road safety impact assessment or network screening. The review is structured along the following sections, given by the hierarchical steps of developing and applying CPMs:

1. Data collection, sample size and time period
2. Road network segmentation
3. Selection of explanatory variables
4. Model function forms and other statistical considerations
5. Model validation
6. Using CPMs in network screening
7. Using CPMs in developing crash modification factors (CMFs)
8. Using CPM tools

Previous reviews related to CPMs (e.g. OECD, 1997; Lord & Mannering, 2010; Yannis et al., 2015; Basu & Saha, 2017) usually considered some of these steps only, mainly 3 and 4. The presented review fills the gap by compiling information on all six steps, followed by summarised challenges and opportunities, with available solutions.

Review

CPMs express the expected crash frequency and/or severity of a site (e.g. road segment or intersection) as a function of explanatory variables. These variables (risk factors) describe exposure and other characteristics, related to cross section, road design and other attributes. The typical model form is:

$$crash\ frequency/year = \exp(\beta_0) \cdot (exposure)^{\beta_i} \cdot \exp(\textstyle\sum_{i=2}^{n}(\beta_i \cdot x_i)) \qquad (1)$$

where x_i are explanatory variables, β_0 is intercept and β_i (i = 1, 2, …) are regression coefficients. The coefficients cannot be estimated by the traditional ordinary least squares. In order to correctly consider discrete and non-negative character of crash frequencies, and their negative binomial probability distribution, generalized linear modelling (GLM) methods are typically used.

For crash data, the variance (dispersion) typically exceeds the mean: they are overdispersed. The degree of overdispersion in a negative binomial model is represented by overdispersion parameter that is estimated during modelling along with the regression coefficients of the regression equation. The overdispersion parameter is used to determine the value of a weight factor for use in the empirical Bayes (EB) method. This method combines expected (modelled) and recorded (observed) crash frequencies, in order to improve reliability of a specific site safety level estimation (Hauer, 1997). Applications of EB methods are described in later sections of the review.

CPMs may be used for various tasks:

1. to explore and compare combinations of individual risk factors
2. for network safety screening (also known as safety ranking or identification of black spots)
3. for impact assessments, i.e. assessing safety of contemplated (re)constructions
4. for economic analysis

It is to be noted that Task 1 is rather research-oriented; Tasks 2, 3 and 4 represent typical practical tasks.

Given the range of potential applications, CPMs have been acknowledged worldwide as recommended tools, on which rational road safety management should be based. However, at the same time, it has been known that prediction modelling is not a simple task (Turner, Durdin, Bone, & Jackett, 2003; Eenink, Reurings, Elvik, Cardoso, Wichert, & Stefan, 2008; Elvik, 2010) and involve various analytical choices, which are often done without explicit justification. This may explain why there are gaps between state-of-the-art and state-of-the-practice; and this may in turn limit the practical use of CPMs. For example, a survey among European road agencies found that 70% of them rarely or never systematically use CPMs in their decision-making (Yannis et al., 2014).

According to a review of North American practices (Persaud, 2001), network screening is the most common application of CPMs. In Europe, cost-benefit analysis was identified as a common use of CPM application (Yannis et al., 2014).

Regarding the selection of research for inclusion in the review, another distinction needs to be made. In 2010, American Association of State Highway and Transportation Officials (AASHTO) published the first edition of Highway Safety Manual (AASHTO, 2010), which introduces a set of CPMs (referred to as safety performance functions, SPFs, in the HSM) and crash modification factors (CMFs). Crash prediction in the HSM has two main two steps: (1) prediction of a baseline crash rates using SPFs/CPMs for nominal route and intersection conditions, and (2) multiplying the 'baseline' models by crash modification factors (CMFs) to capture changes in geometric design and operational characteristics (deviations from nominal conditions). This approach has gained popularity, being incorporated into Interactive Highway Safety Design Model (IHSDM), recently adopted in the European CPM (Yannis et al., 2015), and used in the New Zealand Crash Estimation Compendium (NZTA, 2016).

The CPMs/SPFs in the HSM and ISHDM, developed from data in several US states, are not directly transferable to other jurisdictions (inside or outside US). Some studies confirmed good transferability, mainly between US states (Sun, Li, Magri, & Shirazi, 2006; Xie, Gladhill, Dixon, & Monsere, 2011; Bornheimer, Schrock, Wang, & Lubliner, 2012), but some were less successful when applied abroad, for example in Canada, Italy or Korea (Persaud, Lord, & Palmisano, 2002; Kim, Lee, Choi, Choi, & Choi, 2010; Persaud et al., 2012; Sacchi, Persaud, & Bassani, 2012; Young & Park, 2013). Therefore, it is recommended that each country and jurisdiction (e.g. State) develop their own specific CPMs. The present review, written by non-US authors, adopts this perspective.

Data collection

In a theory, to obtain sufficiently representative models, one should randomly sample from the population of similar road types or intersections. In this regards, given the variance of crash frequencies, several authors recommended minimal sample sizes, such as at least 50 sites (Turner et al., 2003), 200 crashes (Jonsson, 2005) or 300 crashes (Srinivasan, Carter, & Bauer, 2013). The HSM (AASHTO, 2010) advises using a sample of 30–50 locations with a total of at least 100 crashes per year. However, others were critical about the one-size-fits-all approach. For example Lord (2006) provided guidance on necessary sample size based on sample mean, i.e. for example 200 segments in case of average of 5 crashes per segment, or 1000 segments in case of average of 1 crash per segment. (Note that these considerations do not apply in case of network screening, whose goal is to screen the complete network.)

Data on crashes, traffic volumes and potentially other factors need to be assigned to all the sample sections/sites. Crash data are known for various biases, such as underreporting, location errors, severity misclassification or inaccurate identification of contributory factors. Also traffic volume data may be prone to errors: typical measure of traffic volume AADT is an average, it is an aggregate of various vehicle types (Elvik, 2010).

Choice of time period for crash and AADT data requires another decision. A 1- to 5-year period is usually recommended for safety ranking, with 3-year period being the most frequent (Elvik, 2008). Using longer time periods (beyond five years) may cause problems due to changes in conditions, such as a substantial increases in traffic volumes or layout changes, over the time period. Probably due to these issues there are no specific guidelines for time period choice. An exception was the simulation study of Cheng & Washington (2005) which concluded there is little gain in the network screening accuracy when using a period longer than 6 years. Also using several consistency tests, 4 years were found sufficient for developing a CPM in a study by Ambros, Valentová, & Sedoník (2016). Usually a compromise between the need for early analysis of new treatments and the need for accumulating sufficient crashes to permit analysis is accepted (Elvik, 2010).

Regarding data collection, differences between rural and urban settings are also worth mentioning. Traditionally most focus has been given to rural roads (as also evident from CPM reviews by Reurings, Janssen, Eenink, Elvik, Cardoso, & Stefan, 2005 or Yannis et al., 2014, 2015), as is also the focus of the present paper. In contrast, modelling urban safety is more challenging, due to higher presence of vulnerable road users and complex environments, including facilities for different road users, mixed land use or higher density of various intersection types, such as those signalised or with a roundabout layout.

Ideal data sources are road agency asset inventories. Unfortunately, they may not be complete, and a modeller thus needs to combine various data sources into the geodatabase on their own. Additional surveys are also conducted, either in the field (pedestrian exposure, visibility, speed, etc.) or via online maps. Recent emergence of big data and open government policies (e.g. open data initiatives such as data.vic.gov.au) have aided these efforts substantially; it is feasible to pull together substantial amounts of road data from publicly available and road agencies' own sources.

Road network segmentation

CPMs are typically developed either for road intersections or segments. In the latter case, segmentation has to be conducted, in order to divide the network into homogeneous segments, i.e. with constant values of explanatory variables. However, in case of multiple variables, this practice can naturally lead to short segments, which may for example complicate assigning crashes. Some authors set fixed segment lengths of several hundred meters (Cenek, 1997; Geyer et al., 2008; da Costa, Jacques, Pereira, Freitas, & Soares, 2015), or used patterns based on tangents and curves (Koorey, 2009; Turner, Singh, & Nates, 2012; Cafiso & D'Agostino, 2013). On the other hand, for network screening, longer segments (1 – 5 km) are often used (Ragnøy, Christensen, & Elvik, 2002; Pardillo Mayora, Bojórquez Manzo, & Camarero Orive, 2006; Gitelman & Doveh, 2016).

Explanatory variables

Selection of explanatory variables should be guided by previously documented crash and injury risk factor evidence available from research literature. However, in practice it is often dictated simply by data availability. Explanatory variables generally include exposure, transport function, cross section, traffic control; less often variables describing alignment or road user behaviour are used (Reurings et al., 2005). When actual variables are not available, proxy variables may be used, e.g. abutting land use as a proxy for pedestrian movement counts.

In order to identify the statistically significant variables, a stepwise regression approach is typically used. It may be applied either in a forward selection or a backward elimination manner; in both cases selected goodness-of-fit (GOF) measures are used to assess the statistical significance.

Common GOF measures include information criteria such as AIC or BIC, while others use for example scaled deviance (Fridstrøm, Ifver, Ingebrigtsen, Kulmala, & Thomsen, 1995; Turner et al., 2003) or proportion of explained systematic variance (Kulmala, 1995; Ambros et al., 2016).

Based on a number of explanatory variables (model complexity), CPMs may be simple (exposure-only) or multivariate (fully-specified) (Persaud, 2001). Sawalha & Sayed (2006) warned against temptations to build overfit models, i.e. containing too many insignificant variables. In fact, a number of studies found that additional predictors are not as beneficial as expected (Peltola, Kulmala, & Kallberg, 1994; Wood, Mountain, Connors, Maher, & Ropkins, 2013; Saha, Alluri, & Gan, 2015). One should strive for parsimonious models, i.e. the ones containing as few explanatory variables as possible (Reurings et al., 2005). Such models enable simple interpretation and understanding, as well as easy updating (Ambros et al., 2016).

On the other hand, in case of leaving out an influential explanatory variable due to unavailable data, so called “omitted variable bias” occurs. The bias results in biased parameter estimates that can produce erroneous inferences and crash frequency predictions (Lord & Mannering, 2010; Mitra & Washington, 2012; Mannering & Bhat, 2014).

Model function forms and other statistical considerations

Before modelling itself, exploratory data analysis should be conducted, in order to detect potential outliers, check the extreme values, potential mistakes, etc.

Crash frequency (i.e. response variable) ideally should not involve mixed levels of crash severity and crash types, as it may produce uninterpretable results (Elvik, 2010). It is thus recommended to develop disaggregated CPMs (Reurings et al., 2005). Alternatively one may use the observed proportion of a given crash type or severity and apply it to the CPM that has been estimated for total crashes (Srinivasan & Bauer, 2013). However, this has been found a questionable practice, leading to estimation errors (Jonsson, Lyon, Ivan, Washington, van Schalkwyk, & Lord, 2009). The current recommendation is estimating separate CPMs by crash types. New Zealand practice is developing models for key (or common) crash types and, if necessary, scaling their predictions to represent total crash frequency (Turner et al., 2003), to allow for less common crash types. Some studies (Garach, de Oña, López, & Baena, 2016; Gitelman & Doveh, 2016) used sub-samples (for example stratification based on AADT under/over specific limits) in order to improve model quality. In any case, developing disaggregated CPMs obviously requires larger sample sizes. In terms of severity either models are developed by severity levels (usually with fatal and serious injury crashes combined), as with the ANRAM models (Jurewicz, Steinmetz, & Turner, 2014), or severity factors (proportions) are applied to models developed for all injury crashes (NZTA, 2016) or all crashes (including non-injury).

To select the most suitable mathematical forms of explanatory variables, one may use graphical relationships to crash frequency (Arndt & Troutbeck, 2006), or use more complex techniques, such as empirical integral functions and cumulative residuals (CURE; Hauer & Bamfo, 1997). According to Hauer (2004), the model equation may have both multiplicative components (to represent the influence of continuous factors, such as lane width or shoulder type), and additive components (to account for the influence of point hazards, such as driveways or narrow bridges). Despite these recommendations, the typical modelling approach is often simple. The general model form of equation (1) is widely adopted. Exposure is usually modelled in terms of traffic volume, i.e. single AADT value for road segments, or product of major and minor AADTs for road intersections.

There is no universal guidance and various function forms are used in the literature. For example, traffic volume is typically used in a power form, but some authors considered it jointly with an exponential form (so called Ricker model; Roque & Cardoso, 2014). Another example is segment length, usually applied as an offset, i.e. with regression coefficient = 1, but often also in a power form (Hadi, Aruldhas, Chow, & Wattleworth, 1995; Reurings & Janssen, 2007; Roque & Cardoso, 2014).

According to Hauer (2001), segment length should also be considered when estimating the over-dispersion parameter to be used in the empirical Bayes approach. However, the exact form of the relationship is not definite (Cafiso, Di Silvestro, Persaud, & Begum, 2010); in fact, not only length but also other variables may play a role (Geedipally, Lord, & Park, 2009).

Model validation

The goal of validation is proving whether the developed model is acceptable from both scientific and practical perspective. It is thus surprising that most of modelling guidelines seem to overlook this step (Maher & Summersgill, 1996; Hauer, 2004, 2015; Sawalha & Sayed, 2006; Wood & Turner, 2007; AASHTO, 2010; Srinivasan & Bauer, 2013; Fridstrøm, 2015).

According to Oh, Lyon, Washington, Persaud, & Bared (2003), one may distinguish between internal validity (agreement with theoretical expectations and past research) and external validity (goodness-of-fit). The latter may be evaluated by comparing either models from two independent samples, or a model from a complete sample applied on selected sub-samples that have not been used in the model building.

Using CPMs in network screening

Previous reviews (Elvik, 2008; Montella, 2010) indicated that current practices are "not close to the state-of-the-art". According to the EB method, CPMs should be used and their results (expected crash frequencies) combined with crash history (observed crash frequencies) to obtain so called "expected average crash frequency with empirical Bayes adjustment" (in short EB estimate). Apart from EB estimates, other variants exist, for example:

- Potential for safety improvement (PSI), which represents the difference between EB estimate and expected frequency, i.e. the potential safety savings (Persaud et al., 1999).
- Level of service of safety (LOSS), which labels the sites into four classes, based on deviations between observed and expected crash frequencies (Kononov & Allery, 2003).
- Scaled difference, i.e. the difference between the observed and predicted crash frequencies, divided by the predicted standard deviation of the crash frequency (Butsick, Wood, & Jovanis, 2017).

In Australia and New Zealand, where low-volume rural roads generate very low numbers of crashes per kilometre (or zero), CPMs can provide a continuous proxy measure of safety. In Australia the ANRAM model uses EB estimates of severe casualty crashes to remove the random variation in observed crash data: sites are prioritised simply on the EB estimate (Jurewicz et al., 2014).

Given the variety of available methods, the Highway Safety Manual (AASHTO, 2010) notes that "using multiple performance measures to evaluate each site may improve the level of confidence in the results." Hence sites may be ranked for treatment based on several different methods (Montella, 2010; Yu, Liu, Chen, & Wang, 2014; Manepalli & Bham, 2016). Those that rank consistently high using several methods are the sites where treatment should be focused.

Using CPMs in developing crash modification factors

Crash modification factor (CMF) is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. CMFs may be derived from before-after or cross-sectional studies; however, each method has its own challenges, and obtained

CMFs can thus often highly inconsistent (Gross, Persaud, & Lyon, 2010). Before and after studies are generally the preferred source of CMFs, particularly for the HSM. However they typically only look at features in isolation and so when the combined effects of features on crash occurrence is not the sum of the effects of each individual feature, then they may provide misleading results. Several solutions to developing multiple treatment CMFs have been proposed, without reaching definite conclusions (Elvik, 2009; Gross & Hamidi, 2011; Park, Abdel-Aty, & Lee, 2014).

Cross-sectional studies (i.e. the ones based on CPMs) have been criticised for being more prone to non-causal safety effects, due to bias-by selection (Elvik, 2011; Carter, Srinivasan, Gross, & Council, 2012; Hauer, 2015). Bias-by-selection can occur when a treatment (like a cycle lane or crash barrier) is applied more often to sites that already have a crash problem than to those that do not. They do however provide a much better crash prediction for the combination of road features. In some cases CMFs are developed from CPMs where limited before and after studies are available.

Using CPM tools

The above-mentioned analytical steps (data preparation, exploratory analysis, modelling, calculations) are typically conducted in statistical software or spreadsheets. Nevertheless, for an end user it is beneficial to be able to visualize the results. These may take form of tables or map outputs, for example the identified hotspots or the lists of ranked segments.

One option is using stand-alone software solutions, such as the following two from the USA:

- IHSDM Crash Prediction Module estimates the frequency and severity of crashes on a highway using geometric design and traffic characteristics. This helps users evaluate an existing highway, compare the relative safety performance of design alternatives, and assess the safety cost-effectiveness of design decisions. (FHWA, 2003)
- SafetyAnalyst (commercial software) Network Screening Tool identifies sites with potential for safety improvement. In addition, it is able to identify sites with high crash severities and with high proportions of specific crash types. (FHWA, 2010)

Note that there are close links between IHSDM, SafetyAnalyst and Highway Safety Manual. According to Harwood, Torbic, Richard, & Meyer (2010), SafetyAnalyst Module 1 (network screening) is to be applied first, followed by Module 2 (diagnosis and countermeasure selection), Module 3 (economic appraisal and priority ranking) and IHSDM to perform safety analyses as part of the design process.

The Finnish evaluation tool TARVA also deserves mentioning. Its purpose is to provide a common method and database for (1) predicting the expected number of crashes, and (2) estimating the safety effects of road safety improvements (Peltola, Rajamäki, & Luoma, 2013). Based on simple CPMs and pre-determined CMFs, it currently exists in Finnish and Lithuanian versions, with planned applications in other countries.

Capabilities of network screening and road safety impact assessment are also built in commercial software PTV Visum Safety (http://vision-traffic.ptvgroup.com/en-us/products/ptv-visum-safety/).

There are also applications in the form of Excel spreadsheets, for example British COBALT, Swedish TS-EVA or Norwegian CPMs for national and country roads (Høye, 2014, 2016). In the US, spreadsheets were developed for safety analysis of freeway segments and interchanges (ISAT: Torbic, Harwood, Gilmore, & Richard, 2007; ISATe: Bonneson, Geedipally, Pratt, & Lord, 2012).

The Australian National Risk Assessment Model (ANRAM) tool, available to road agencies, is a network screening and prioritisation tool which uses CPMs for different road stereotypes, together with CMFs and observed crash data to estimate severe injury crashes across segmented road network (Jurewicz et al., 2014). ANRAM allows users to develop and estimate benefits of road network and corridor treatment programs. This tool has gained wide use among state road agencies in Australia, particularly for the rural road networks where actual severe crashes are randomly distributed. ANRAM is available in a spreadsheet form, with planned online adaptations.

New Zealand also has a history of various safety prediction tools. Turner, Tate, & Koorey (2007) stressed the practical need of such tools and after review of overseas applications, considered IHSDM as worth transferring into New Zealand conditions, for assessing new road designs. A later work (Turner & Brown, 2013) reviewed New Zealand spreadsheet applications, as well as experience with using and calibrating the ISAT tool from the USA.

Challenges and opportunities

The review indicated various challenges, as well as opportunities and solutions for the mentioned issues. They are briefly summarized in the following paragraphs.

Data collection

Sample sizes are the limiting factor. Unlike in the case of large USA and Canadian samples, smaller countries are limited in their samples of network and crash data. For example, Turner et al. (2003) mentioned, that New Zealand road network size limits the development of models for some segment and site types, e.g. interchanges. This factor also reduces chances of disaggregation CPMs into all crash types and severity levels. In addition, there is no universal guidance either on necessary sample size, or recommended time period for crash data.

Road network segmentation

Division of road network into segments is likely to be dictated by structure of national road databanks. For example in the Czech Republic, national traffic census (as the main source of AADT data) does not cover all minor roads; thus process of aggregating segments into longer segment including minor intersections was found feasible (Ambros, Sedoník, & Křivánková, 2017a). As the segments may be subject to further investigations, their length should be feasible for on-site visits or crash analyses.

Use of long road segments, e.g. matching measured AADTs, can lead to loss of meaningful responsiveness to variables of interest to practitioners. Long segments are more likely to contain multiple design scenarios, e.g. pavements of different widths or multiple curves. Shorter segments are more likely to identify such changes and measure their influence. This is offset by loss fidelity of AADT and crash data location. This issue requires some optimisation based on experience with available data.

Explanatory variables

Network-wide data availability is again the guiding principle. Additional data collection is usually costly and limiting in perspective of future updating. For most practical applications, such as network screening, simple models (exposure-only) have been found sufficient (Srinivasan & Bauer, 2013). A practice-driven approach was adopted in developing New Zealand rural road CPMs (Turner et al., 2012); when it was found that the statistically significant variables did not include the parameters that were of most interest to practitioners, two distinct models were developed: statistical models (best performing models according to GOF measures at 95% confidence levels) and practitioners' models (containing also additional variables of interest to safety professionals, at confidence levels of 70% or more).

Model and function forms

Simple CPM form (Equation 1) is used the most often. Traffic volumes (flows) should be adapted to the specific segment and intersection types. For example, New Zealand CPMs (NZTA, 2016) apply either product of flows or conflicting flows, based on the type of intersection, urban/rural settings and speed limits.

Model validation

The developed CPMs should be validated, either by comparing models from two independent samples, or comparing a model from a complete sample to the models based on selected sub-samples (not used in the modelling). However, this practice is probably seen as difficult, since most guidelines do not mention this step.

Using CPMs in network screening

Network screening should be based on empirical Bayes (EB) method, which combines CPM predictions with observed crash frequencies to assess and rank the sites. There are several different methods; EB estimates and potential for safety improvement (PSI) are used the most often.

Using CPMs in developing crash modification factors

Although the practice of deriving crash modification factors (CMFs) from cross-sectional CPMs has been criticised, it is relatively common. Again there are various approaches: for example Park et al. (2014) tested six different methods of combining CMFs and concluded that one should not rely on only one of them. Interim solution is applying 'rule-of-thumbs', such as using the product of no more than three separate independent countermeasures (OECD, 2012) or reducing the product through multiplying by a ratio 2/3 (Turner, 2011).

Using CPM tools

Several tools for modelling and visualization exist; probably the most easy-to-use are spreadsheet applications. When implemented online (such as Finnish TARVA or planned version of Australian ANRAM), they enable periodical updates, as well as joint use of other online data sources.

Increasingly, online business analytics software has been used to display CPM results in map format, often with dynamic filtering and computational functions. Examples include open source and free resources such as ArcGIS Online, QGIS, Tableau, or Microsoft Power BI. These solutions make it easy for practitioners to access and understand the value of CPMs.

Summary and conclusions

A number of steps have been reviewed: from data collection and road network segmentation to choosing variables and function forms, validating models and using them in practice, including description of available tools. From the review it is obvious that developing CPMs is not a straightforward task: there is a number of available choices and decision during the process (without definite guidance), which explains the diversity of approaches and techniques, as well as resulting models developed worldwide. While this may be interesting from a research perspective, it definitely limits understanding and application by practitioners, and complicates international comparability or transferability. There is a need to identify the solutions, which will be scientifically sound and valid, while also feasible with regards to real-life conditions and needs.

The main point is that the end users of CPMs are the practitioners, i.e. road agencies, which "cannot always afford the luxury of doing state-of-the-art crash modelling" (Elvik, 2010). The review aimed to answer the original questions, how and why should they consider using CPMs? The answers may be following:

- CPMs are valuable tools, which help link crashes with risk factors. This is especially valuable in current conditions of scattered crash occurrence (less crash black-spots), where traditional crash-based approaches do not work well.
- Developing and using CPMs has its challenges (as described above). However, these may be minimised by increased communication between researchers (who develop CPMs) and users (agencies), resulting in easy-to-use tools. However it is important that these tools do not become black-boxes, and that users do have a basic understanding of CPMs and CMFs, and that local CPMs and CMFs can be used in the tools (or that there is a method to calibrate the CPMs and CMFs to local conditions).
- Applying network-wide CPMs enables performing effective road safety impact assessment and network screening.

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