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Estimation of the influence of protective behaviour on expected injuries in transport accidents with hazardous materials

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ABSTRACT

The release of hazardous materials due to transport accidents can have major health consequences for bystanders. The number of casualties will partly be determined by their protective behaviour.

This study describes a three-step approach to predict health consequences of protective behaviour (for example, hiding or escaping) of bystanders in the first minutes of a transport accident with hazardous material. First, a discrete choice experiment (DCE) was used to predict protective behaviour. Second, a gas dispersion model (SeReMo) was used to estimate the distribution of casualties for different protective behaviours. Third, results of the DCE and SeReMo were combined to estimate the distribution of casualties in the population-at-risk. This approach was applied to a hypothetical marine accident with different hazardous material scenarios on a large waterway in a close vicinity of a beach/quay with bystanders.

An important finding of our study was that in general a short reaction time and escaping in cross-wind direction, as protective behaviours, are of vital importance to reduce the number of casualties. A scenario with a short reaction time and a visible cloud towards the beach/quay resulted in a protective behaviour with the largest reduction of casualties.

A dynamic risk assessment approach considering that people threatened by hazardous material are not 'stationary observers', but will exhibit protective behaviour, and a risk assessment that takes into account empirical information on expected protective behaviour will present a more realistic estimate of the number and severity of casualties when a large transport accident with hazardous materials would occur.

1. Introduction

Transport accidents with hazardous materials in a populated area can have major consequences. For example, in 2009 a derailment of a freight train carrying 14 LPG (liquefied Petroleum Gas) tank-cars near Viareggio, Italy, caused a massive LPG release near residential buildings and the trigged flash-fire resulted in 31 deaths [1]. In 1976 a road tanker fell from a bridge in Houston, USA, after which the toxic ammonia gas was released that resulted in 200 injured persons and 6 deaths [2].

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When a transport accident with a hazardous material occurs in close vicinity of a populated area, hazardous material may release and expose bystanders within minutes. It is unlikely that local authorities can respond in this short time window by activating the civil defence siren or initiating a guided evacuation by emergency services. Thus, the number of casualties will partly be determined by patterns of protective behaviour in population-at-risk. Two main strategies undertaken by the general public are seeking shelter or leaving the area at risk. In general, people will not act on threat information unless they perceive a personal risk to themselves and, contrary to widespread belief, escaping in panic rarely occurs [3]. The protective behaviour in an acute chemical emergency will be influenced by differences in chemical characteristics (destructive potential and controllability) and variations within the social context (e.g. demographic characteristics of population-at-risk) of that particular situation [4]. Perceptions of risk can inform and influence behaviour in response to a perceived risk [5]. The public's threat perception of chemical agents is quite often inaccurate, probably because a lack of an experiential point of reference [4,6].

A general framework for people's responses to environmental hazards and disasters has been delineated in the Protective Action Decision Model (PADM) by Lindell and Perry [7]. In short, this model describes the process of individual responses to environmental hazards and disasters, from the reception of social and environmental cues and information about a hazard or disaster to psychological processes (predecision processes, perception, and protective action decision-making) that in turn will produce protective behaviour. The process starts with environmental cues (e.g. sights, smells, or sounds that signal the onset of a threat), social cues (e.g. seeing others escaping), and warnings (e.g. siren). The environmental cues will not lead to the initiation of appropriate protective actions unless people are exposed to, heed, and accurately interpret the environmental cues. The cues and warnings initiate perceptions of environmental threat which subsequently guide protective behaviour. The behavioural response will be influenced by personal characteristics (e.g. physical, psychomotor and cognitive abilities), situational facilitators (e.g. shelters), and impediments (e.g. separation of family members). A highly credible (or powerful) source might obtain immediate and unquestioned compliance with a directive to evacuate an area at risk, as opposed to when there is greater ambiguity. The PADM is a highly used model in environmental hazards and disasters studies. For example, the protective action decision model was integrated in a study to understand what motivates nuclear not-in-my-backyard (NIMBY) behaviour and how information acquisition, perception of risk, benefits, and knowledge, and the NIMBY attitude influenced behavioural response [8]. A questionnaire survey applied PADM to explain flood preparedness intentions in the Netherlands [9]. A repeated cross-sectional study of residents in a high-risk (chemical release) petrochemical manufacturing community investigated whether PADM core risk perceptions predicted protective action decision making [10]. A study in China investigated hazardous chemicals risk of urban residents with a Response Action Decision Model based on the PADM [11].

In most accident models the number of victims in a transport accident with hazardous substances will depend on the exposure and the risk associated with that exposure. The following sources of hazardous substances are usually distinguished: (i) dispersion of toxic gases, (ii) dispersion of combustible gases followed by an explosion, and (iii) dispersion of combustible gases followed by a fire. The evaluation of the consequences of hazardous gases typically consist of four steps: (i) source term estimation, (ii) dispersion modelling, (iii) hazardous gas concentration estimation, and (vi) impact of the hazardous gas concentration on health of exposed people [12]. To address the last step several approaches haven been introduced in literature such as Fractional Incapacitating Dose (FID) and Fractional Irritant Concentration (FIC) for chemicals that have a dose related threshold for sublethal injuries and chemical that have a concentration related threshold, respectively [13–15]. This type of risk assessment can be further improved by including the impact of protective behaviour and people movements during emergencies, as traditional models assume a 'stationary observer' [16]. Hence, in risk assessment for disasters involving toxic or combustible gases, both gas dispersion patterns in the area and protective behaviour of bystanders (shelter or evacuation trajectory) should be taken into account. A recent accident model that takes the aforementioned points into account is the Self Rescue Model (SeReMo) [17]. It has an injury model for toxic chemicals that differentiates between chemicals with a dose related threshold for sublethal injuries and chemicals with a concentration related threshold, and additional injury models for heat radiation and explosion (overpressure). SeReMo also quantifies the effects of the protective behaviours 'taking shelter' and 'escape' [18,19]. The latter is based on assumptions on protective behaviour of the population in case of an accident. To the best of our knowledge there are no other studies that have examined the protective behaviour of bystanders and applied this information in dynamic gas exposure modelling to estimate the number of victims.

Hence, the aim of this study is to introduce a methodology to 1) to predict people's intended behaviour in the first minutes of a transport accident with hazardous materials and to quantify how different environmental and social cues, and perceptions threats will influence protective action decision making, 2) estimate the burden of injuries of the different (dynamic) protective behaviours, and 3) estimate the burden of injuries in a study population for different scenarios, taking into account people's predicted protective behaviour. In this study the methodology has been applied to a hypothetical marine accident on a large waterway in close vicinity of a beach/quay. On many waterways in the world transport of hazardous material takes place in close vicinity of beaches and quays. The probability of a hazardous material accident by collision between two ships is very small, but the consequences could be severe for persons in the vicinity of the accident. With the findings of this study, policy makers can take safety measures to prevent or reduce the number of victims in case of an accident involving hazardous substances.

2. Methods

2.1. Study design

In this study a hypothetical marine accident with hazardous materials on a large waterway in the direct vicinity of a beach/quay and its consequences for health of bystanders were investigated. The study consists of three parts. The first part is a questionnaire among inhabitants living in the direct vicinity of a large waterway where hazardous materials are transported. The questions relate to health, risk perception, and protective behaviour during an accident. With a discrete choice experiment (DCE) the intended behaviour of respondents, i.e. staying, seeking shelter, or escaping, was determined for different accident scenarios. The questions in the survey and the design of the DCE were based on determinants of the PADM. Two focus group discussions with the general population living in the direct vicinity of a large waterway in the Netherlands (six and seven participants, respectively) provided information for the selection of most important PADM determinants. The second part of the study consists of a structured health impact assessment with the Self Rescue Model (SeReMo). For the different protective behaviours the lethal and sublethal injuries in the case of a toxic and a combustible gas scenario were estimated. In the third part of the study the burden of injuries in the specific study population was estimated for the different accident scenarios, taking into account people's predicted protective behaviour.

The municipal Public Health Services in the Netherlands are required by law to regularly monitor the health of the local population. A postal questionnaire was send, together with an information leaflet explaining that informed consent was provided by returning a filled out questionnaire. Under the Dutch law for medical scientific research with human subjects questionnaire surveys are not subject to approval by an institutional ethics committee. Data protection and privacy was in adherence to the Code of Conduct for Medical research (at www.federa.org), established by the Council of the Federation of Medical Scientific Societies.

2.2. Study locations and scenarios

The study location was the beach/quay of two cities (Terneuzen and Vlissingen) across a large waterway (Westerschelde) in the Southwest of the Netherlands (see Fig. 1).

Since shipping of large quantities of ammonia (toxic) and propane gas (combustible) took place, these hazardous materials were selected for further evaluation. Propane is odorized by mercaptan. Mercaptan has a typical gas odour which has a familiar smell for Dutch people. The scenarios start with a collision between two ships that will release a toxic ammonia cloud or a combustible propane gas cloud. Both ammonia and propane form a visible cloud (mist) that is initially located around the ship and then floats to the beach/quay. At the moment the cloud reaches the beach/quay, sensory perception is assumed by a strong ammonia or gas odour. The following protective behaviour options were evaluated: staying, sheltering, escaping by walking in along-wind direction, escaping by walking in cross-wind direction, escaping by running in along-wind direction, and escaping by running in cross-wind direction. Fig. 2 shows the main strategies for self-rescue behaviour in this study population. Bystanders may exhibit a delayed response to an accident. Therefore, the following reaction time possibilities were evaluated: short reaction time (i.e. people start to react about 10 s after the collision, based on sound and visibility of the accident) and long reaction time (i.e. people start to react 10 s after they perceive the ammonia or propane (mercaptan) odours.

In summary, in this study 4 scenarios were defined, based on accident characteristics and reaction time, with different protective behaviours within each scenario (see Table 2).

2.3. Questionnaire

A cross-sectional study was conducted among inhabitants (aged 19–64 years) of the two study locations. The respondents were recruited from the neighbourhood where the hypothetical marine accident takes place and therefore are familiar with the local situation including the buildings for shelter. The questionnaire consisted of two main parts, namely: 1) questions on socio-demographic characteristics, health, risk perception, and protective behaviour, and 2) Discrete Choice Experiment (DCE) questions.

2.3.1. Questionnaire on socio-demographic characteristics, health, risk perception and protective behaviour

Besides socio-demographic characteristics (gender, age, household composition and education, see Supplementary Text, File A) physical fitness, risk perception, and some aspects of protected behaviour were included. Physical fitness was measured with a single question to determine six levels 1) I can run for 5 min or more without problems, 2) I can run for 1–5 min, but not longer, 3) I can run for a short time, not longer than 1 min, 4) I cannot run at all but easily walk 300 m, 5) I cannot run at all and also not easily walk 300 m, and 6) I am dependent on others. Risk perception was measured by an 11 point scale on level of concern about potential impacts of living near a waterway on their safety (0: not worried at all, 10: extreme worried). A respondent was classified as very worried if he or she gave a value between seven and ten on the risk scale [20]. The question about awareness of the transport of hazardous material

Fig. 1. Shipping along the city Vlissingen, the Netherlands. Photo: Safety Region Zeeland, the Netherlands.

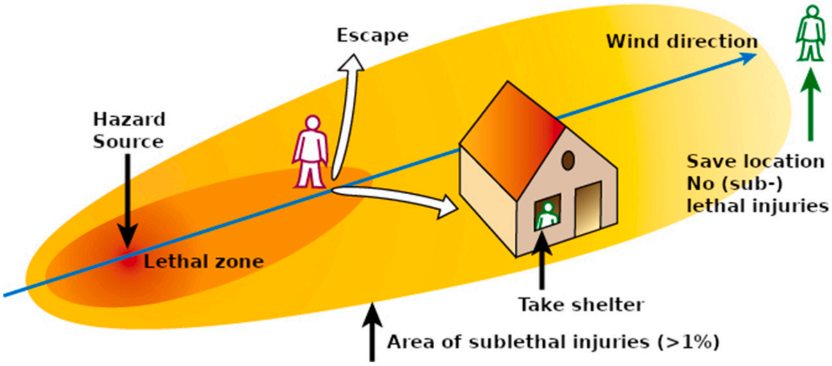

Fig. 2. Main strategies for self-rescue behaviour.

over the river had four possible answers: daily, sometimes, seldom, and never. The association of odour with danger was determined by two questions on associating smell of ammonia or gas with danger with 5-point scale ranging from strongly disagree to strongly agree. A score of (strongly) agree was categorized as a participant who associates smell with danger. The question on escape direction relative to wind direction had four possible answers: along-wind, cross-wind, against the wind, and I do not know. In this study we did not consider the option that persons would approach the site of the accident and, therefore, the answer 'against the wind' has been interpreted as missing. Finally, a question was asked on how fast someone will escape with seven possible answers: 1) walking to a safe distance, 2) running to a safe distance, 3) walking to your car and drive to a safe place, 4) running to your car and drive to a safe place, 5) walking to your bike/moped and drive to a safe place, 6) running to your bike/moped and drive to a safe place, and 7) miscellaneous behaviours.

The statistical analyses were conducted with the statistical package IBM SPSS version 21 (SPSS Inc., Chicago, IL, USA).

2.3.2. Discrete choice experiment

Part of the questionnaire consisted of Discrete Choice Experiment (DCE) questions. Details of this DCE study were published earlier, see De Bekker-Grob et al. [21]. In short, the DCE is a quantitative technique to investigate individual preferences (choice behaviours). It has a solid foundation in random utility theory [22,23] and includes a Nobel prize-winning econometric approach [24]. It elicits preferences that individuals are willing to make by asking respondents to choose between different options described by their attributes and levels [25–27]. In this quantitative sub-study the intended behaviour of respondents is investigated by presenting different accident scenarios with hazardous material on the river and asking respondents to choose the behavioural alternative that was most appealing to them: staying, seeking shelter, or escaping. The alternatives (stay, hide or escape) were described by the following attributes (characteristics): odour perception, smoke/vapour perception, and proportion of people leaving (see Fig. 3 for a choice set example and Supplementary Text, File A). The attributes were further specified by variants of those attributes (attribute levels). The attribute odour perception had the following five attribute levels: none (reference level), weak ammonia odour, strong ammonia odour, weak gas odour, and strong gas odour. The attribute smoke/vapour perception had the following three attribute levels: none (reference level), around the ship, and towards the ship. The attribute about the proportion of people that are leaving had the following four attribute levels: 0% (reference level), 20%, 50%, and 80%. For a more detailed description of the DCE study we refer to our previous publication [21].

2.4. Self rescue model

The Self Rescue Model (SeReMo) has been developed to predict the consequences of human behaviour on lethal and sublethal

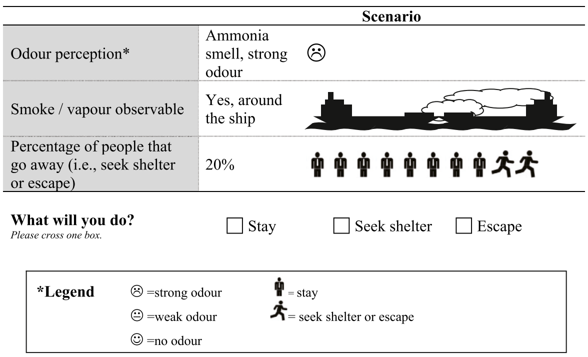

Fig. 3. Example of a choice set.

injuries for toxic and fire/explosion accidents. SeReMo uses the same physical models as the model EFFECTS, described in detail in the 'Yellow Book' [28] and the 'Green Book' [29]. In addition, the SeReMo contains protective behaviour as well as an injury model and a translation of injury to a triage classification, that is used by medical emergency responders to determine the urgency of medical treatment of victims of an accident. For a detailed description of SeReMo, see Trijssenaar [15,17,18,30]. In short, the following aspects were included in the SeReMo model.

Reaction time. The degree of injury depends on level and duration of the exposure. When a collision between two ships takes place, it can take some time before bystanders will react.

Exposure during shelter. The concentration inside the shelter depends on the concentration outside and the degree of ventilation inside and whether windows and doors are closed. When sheltering, it is assumed that the persons are inside during the accident.

Exposure during escape. The strategy escape can be complemented by walking or running in a cross-wind or along-wind direction from the accident. The self-rescue time depends on how fast a person can walk and differs across scenarios, depending on scenarios with exposure to toxic substances or to fire. Running does not only affect the moving speed of a person, but also increases the respiratory minute volume and, thus the inhaled exposure. For toxic injuries a distinction is made between chemicals that have a dose related threshold (i.e. exposure concentration level * duration) and chemicals that have an exposure concentration threshold for injuries. The effects of a vapour cloud explosion are similar to those of a flash fire of a flammable vapour cloud, supplemented by pressure effects as a result of the explosion. For a flammable cloud it is assumed that everyone who is in the effect zone at the moment of ignition will die and outside the effect zone the number of injuries is relatively low [31].

Casualties. SeReMo translates the health effects into three injury classes: death, immediate hospitalisation required (i.e. within 2 h), and urgent hospitalisation required (i.e. within 6 h). These classes are used by medical emergency responders to determine the urgency of medical treatment of victims of an accident [32]. See Supplementary Text, File B for a technical description of the accident and the input parameters used in SeReMo.

2.5. *Casualties per scenario in the study population*

To estimate the burden of casualties in a study population for different scenarios, taking into account people's predicted protective behaviour, the results of the DCE and SeReMo were combined. The distribution of type of casualty (death, immediate hospitalisation, or urgent hospitalisation) for each scenario (strong odour, cloud towards beach/quay, etc.) depends on the protective behaviour of people (staying, seeking shelter and escaping) per scenario (as established in the DCE) and the casualties of each protective behaviour (as predicted in the SeReMo). The distribution of casualties per scenario is calculated by multiplying the results of the DCE (protective behaviour per scenario) with the results of the SeReMo (casualties per protective behaviour).

3. Results

3.1. *Characteristics of respondents*

The response rate to the questionnaire was 44% (881/1994). Table 1 shows the characteristics of the respondents. About 50% of the respondents where between 50 and 64 years old, 26% had a high educational level, and 47% had children. Most of the adults (53%)

Table 1
Characteristics of respondents in who completed the questionnaire (N = 881).

Characteristic	n	%
Gender (male)	415	47
Age groups		
19–34 years	162	18
35–49 years	296	34
50–64 years	423	48
Household with children	404	47
Education level		
Primary school	38	4
Lower general secondary education	266	30
Higher general secondary education	343	39
College, university	227	26
Physical fitness in the case of an emergency		
Can run for 5 min or more	452	53
Can run for 1–5 min	274	32
Can run for less than 1 min	48	6
Can walk for 300 m or less	70	10
Perception		
Very worried about shipping in the neighbourhood	106	12
Associate smell of ammonia with danger	692	80
Associate smell of gas with danger	768	88
Self-rescue behaviour if people escape (n = 613)		
Escape in cross-wind direction, walking	232	38
Escape in cross-wind direction, running	155	25
Escape in along-wind direction, walking	138	23
Escape in along-wind direction, running	88	14

reported to be able to run for 5 min or longer. About 12% were very worried about living along a shipping route, 52% were sometimes or daily aware of the transport of hazardous materials over the river, and most of the adults associated ammonia and propane (mercaptan) odour with danger (80% and 88% respectively). If people had to escape, escaping in cross-wind direction was the option most often chosen (63%).

3.2. Discrete choice experiment

Fig. 4 shows the results of the DCE analysis, compared to the base case. The base case in this study is a mildly looking marine transport accident (i.e., without any odour perception or smoke/vapour perception, and where the bystanders will not leave the location). In this scenario the DCE predicted probabilities that a subject would stay, seek shelter, or escape were 62%, 13%, and 25%, respectively. For a severe looking marine transport accident these probabilities were 1%, 16%, and 83%, respectively, showing a strong shift towards escaping. Escape was much more preferred than seeking shelter. A perception of a strong ammonia odour (compared to the base case) increased the predicted probability that a subject will seek shelter by 9% points or will escape by 40% points, compared to 'no odour perception'. If smoke/vapour came close to individuals, people's preference changed from staying to seeking shelter and escaping.

3.3. Self Rescue Model

Table 2 shows the distribution of casualties for 4 scenarios, based on accident characteristics and reaction time, with different protective behaviours within each scenario.

For the toxic scenario, combined with a long reaction time, the model predicted that sheltering is the only effective action perspective. The escape behaviour (along-wind or cross-wind direction, and walking or running) did not have a positive effect on the

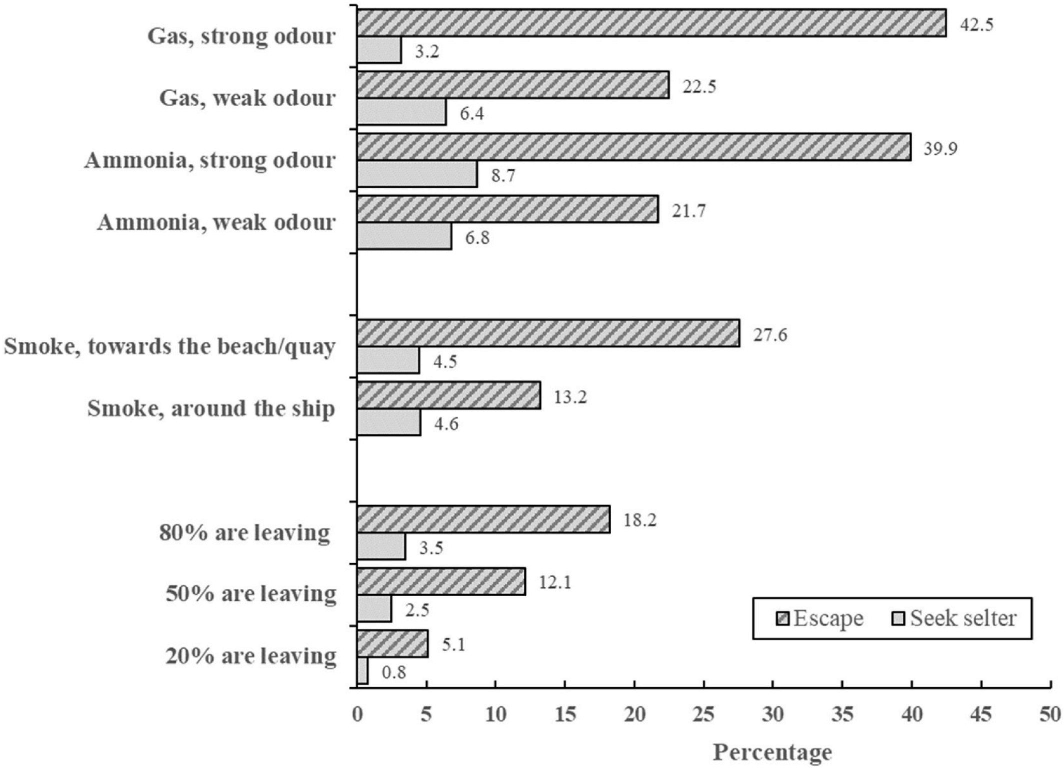

Fig. 4. Effects of changing one of the attribute levels (i.e., univariate marginal estimates) on the average probability of citizens' protective behaviour (seeking shelter or escaping) to transport accidents involving hazardous materials on a populated waterway, as predicted by a panel error component model (n = 881).
Note: the base case is a visible transport accident involving hazardous materials on a populated waterway without any odour perception or smoke/vapour perception, and where 0% of the people in the environment will leave the location at their own discretion. This base case is indicated as zero change in the probability of the x-axis (i.e., equal to predicted probabilities that 61.8%, 12.9% and 25.3% of the persons will stay, seek shelter, and escape respectively) [8].

Table 2
Injury consequences by protective behaviour modelled with SeReMo for toxic scenario (ammonia) and fire/explosion (propane) scenario by short (i.e. people start to react about 10 s after the collision) and long reaction time (i.e. people start to react 10 s after they perceive the ammonia or propane (mercaptan).

	Casualties (%)		
	Death	Hospitalisation	
Scenario		Immediately[a]	Urgently[b]
Toxic scenario (ammonia) and a short reaction time			
Stay	57	43	0
Shelter	8	42	50
Escape in along-wind direction, walking	43	54	4
Escape in along-wind direction, running	20	40	41
Escape in cross-wind direction, walking	0	0	50
Escape in cross-wind direction, running	0	0	0
Toxic scenario (ammonia) and a long reaction time			
Stay	57	43	0
Shelter	8	42	50
Escape in along-wind direction, walking	57	44	0
Escape in along-wind direction, running	57	44	0
Escape in cross-wind direction, walking	57	44	0
Escape in cross-wind direction, running	57	44	0
Combustible scenario (propane) and a short reaction time			
Stay	100	0	0
Shelter	100	0	0
Escape in along-wind direction, walking	45	0	0
Escape in along-wind direction, running	10	0	0
Escape in cross-wind direction, walking	30	0	0
Escape in cross-wind direction, running	10	0	0
Combustible scenario (propane) and a long reaction time.			
Stay	100	0	0
Shelter	100	0	0
Escape in along-wind direction, walking	100	0	0
Escape in along-wind direction, running	85	0	0
Escape in cross-wind direction, walking	100	0	0
Escape in cross-wind direction, running	70	0	0

[a] $\leq$ 2 h.
[b] $\leq$ 6 h.

distribution of casualties. In this situation people were already exposed to a high concentration, so that escaping had no longer any impact. When there is a short reaction time, escaping appeared as an option to limit the distribution of casualties. Running was more effective than walking, despite the fact that one breathes faster during running. If people would escape by running in cross-wind direction, no casualties at all were predicted and this was therefore more effective than seeking shelter.

For the combustible scenario seeking shelter was not an effective action due to secondary fires in the buildings. When people escape, a short reaction time is of vital importance. When people start to escape after a long reaction time, running helps to reduce the severity of injuries.

3.4. *Casualties per scenario in the study population*

Table 3 shows the distribution of casualties in the study population for each scenario, based on the distribution of protective behaviours in the population-at-risk and the distribution of injuries per protective behaviour.

The scenario with a weak/strong odour and a short reaction time (i.e. people start to react about 10 s after the collision), was not applicable because it takes approximately 60–100 s before the cloud will reach the beach/quay (distance ship to beach/quay is 300–500 m, wind speed is 5 m/s). A short reaction is of vital importance, since it will be already too late if one reacts just after the perception of an ammonia or gas odour. The scenarios with a short reaction time and a cloud towards the beach/quay resulted in protective behaviours with the largest reduction of casualties. Visible clouds around the ship and the percentage of people leaving also reduced casualties but to a lesser extent.

Table 3
Effects of changing one of the attribute levels on the percentage injuries due to transport accidents involving hazardous materials on a populated waterway, as predicted by a panel error component model and SeReMo by short (i.e. people start to react about 10 s after the collision) and long reaction (i.e. people start to react 10 s after they perceive the ammonia or propane (mercaptan)) time.

	Casualties (%)		
	Death (ΔDeath)	Hospitalisation	
Scenario		**Immediate** [b] **(ΔImmediate)**	**Urgent**[c] **(ΔUrgent)**
Toxic scenario (ammonia) and a short reaction time			
Base case[a]: no odour, no cloud and 0% leaving	39.4	36.5	13.0
Weak odour	na (na)	na (na)	na (na)
Strong odour	na (na)	na (na)	na (na)
Cloud around ship	31.6 (−7.8)	33.1 (−3.4)	18.2 (5.3)
Cloud toward beach/quay	25.2 (−14.2)	29.9 (−6.7)	22.2 (9.2)
20% leaving	37.0 (−2.4)	35.4 (−1.1)	14.5 (1.6)
50% leaving	33.0 (−6.4)	33.9 (−2.6)	17.4 (4.5)
80% leaving	29.3 (−10.0)	32.0 (−4.6)	19.7 (6.7)
Toxic scenario (ammonia) and a long reaction time			
Base case[a]: no odour, no cloud and 0% leaving	50.5	42.9	6.5
Weak odour	47.2 (−3.4)	42.8 (−0.1)	9.9 (3.4)
Strong odour	46.5 (−4.0)	42.8 (−0.1)	10.6 (4.1)
Cloud around ship	48.7 (−1.8)	42.8 (0.0)	8.4 (1.8)
Cloud towards beach/quay	48.0 (−2.6)	42.8 (−0.1)	9.1 (2.5)
20% leaving	50.1 (−0.4)	42.9 (0.0)	7.0 (0.4)
50% leaving	48.8 (−1.7)	42.9 (0.0)	8.3 (1.8)
80% leaving	48.5 (−2.0)	42.8 (0.0)	8.6 (2.1)
Combustible scenario (propane) and a short reaction time			
Base case[a]: no odour, no cloud and 0% leaving	81.3	0.0	0.0
Weak odour	na (na)	na (na)	na (na)
Strong odour	na (na)	na (na)	na (na)
Cloud around ship	71.3 (−10.0)	0.0 (0.0)	0.0 (0.0)
Cloud towards beach/quay	61.8 (−19.5)	0.0 (0.0)	0.0 (0.0)
20% leaving	78.0 (−3.3)	0.0 (0.0)	0.0 (0.0)
50% leaving	73.6 (−7.7)	0.0 (0.0)	0.0 (0.0)
80% leaving	67.9 (−13.4)	0.0 (0.0)	0.0 (0.0)
Combustible scenario (propane) and a long reaction time			
Base case[a]: no odour, no cloud and 0% leaving	97.6	0.0	0.0
Weak odour	95.7 (−1.9)	0.0 (0.0)	0.0 (0.0)
Strong odour	93.6 (−4.0)	0.0 (0.0)	0.0 (0.0)
Cloud around ship	96.3 (−1.3)	0.0 (0.0)	0.0 (0.0)
Cloud towards beach/quay	95.0 (−2.6)	0.0 (0.0)	0.0 (0.0)
20% leaving	97.2 (−0.4)	0.0 (0.0)	0.0 (0.0)
50% leaving	96.6 (−1.0)	0.0 (0.0)	0.0 (0.0)
80% leaving	95.9 (−1.7)	0.0 (0.0)	0.0 (0.0)

na: not applicable because it takes 60–100 s before the cloud reach the beach/quay.
[a] Equal to predicted victims that 61.8%, 12.9% and 25.3% of the persons will stay, seek shelter, and escape respectively.
[b] $\leq$ 2 h.
[c] $\leq$ 6 h.

4. Discussion

This study on a theoretical marine transport accident showed that 'odour perception', 'smoke/vapour perception', and 'the proportion of bystanders that are leaving at their own discretion' will influence protective behaviours and thereby influence the expected number of casualties due to the accident. Many people only show protective behaviour when environmental cues (e.g. smells, smoke) are observable. A perception of a strong ammonia or propane (mercaptan) odour had the strongest influence on protective behaviour. Smaller effects were found for observation of smoke/vapour and bystanders leaving at their own discretion. Regarding the toxic scenario, escaping by running in cross-wind direction was most effective in the case of a short reaction time while with a long reaction time, escaping was not effective at all. In the case of a toxic scenario with a short response time and a cloud moving towards the beach/quay, more people escape (28% point) and seek shelter (5% points) and, therefore, the number of deaths will be reduced by 14% points. Regarding the combustible scenario, running in cross-wind direction was the most effective in the case of both a short and long reaction time. Sheltering reduced the severity of casualties in the toxic scenario. For the explosion/fire scenario sheltering is not an effective action. A scenario with a short reaction time and a cloud moving towards the shore will result in a protective behaviour with the largest reduction of casualties (the number of deaths will be reduced by 20% points).

This study introduced a risk assessment approach to get insight in how protected behaviour of bystanders to a hazardous materials release will influence the number and severity of casualties. Compared to most other risk assessments, the risk assessment in this study is improved by 1) predicting human protective behaviour which determines to a large extent the severity of casualties, and 2) using a gas dispersion model that takes into account protective behaviour in its estimated distribution of casualties. Protective behaviour was predicted using a discrete choice experiment (DCE). The DCE method allows for predicting heterogeneity in choices, depending on individual characteristics, thus taking into account the composition of the population at risk, and different attributes of the accident, thereby being able to determine which accident characteristics determine behaviour patterns [21]. Despite the fact that DCEs are increasingly being used in public health to explore trade-offs in the general population between different alternative behaviours to reduce health risk [33,34], we found only few accident studies (building evacuation studies) that have used this DCE methodology [35–39]. Lovreglio et all [35] has used a DCE to study building evacuations with the following variables: number of people using an exit, distance of the participant from an exit, presence of smoke and familiarity of the participant with the exit. The results of this building evacuation study cannot be compared with the accident circumstances in our study (e.g. in our study there are no crowded exits). However, visible signs during an accident (smoke) will influence protective behaviours.

In this study we have used SeReMo to model gas exposure, taking into account protective behaviour. Existing risk assessments typically use stationary observers, that do not take into account protective behaviour (sheltering or escaping) and therefore will most likely overestimate the number and severity of casualties. The advantages of SeReMo are that (i) when taking shelter, the ventilation rate in the building is accounted for, (ii) the pattern of protective behaviour among bystanders is introduced as a determinant of exposure, and (iii) the model takes into account that toxic gases may affect the escaping speed. To the best of our knowledge there are no others accident models for calculating number and severity of causalities, besides mortality, that have incorporated these important features. Only Lovreglio et all [16] and Zhang and Chen [40] have used also a dynamic approach for the impact of a toxic gas dispersion on mortality, while considering human behaviour and dispersion of gas in the area. Lovreglio et all [16] applied it to a hypothetical scenario including a ship releasing nitrogen dioxide (NO_2) on a crowd attending a music festival. Similar to our research the dynamic approach resulted in lower exposure to toxic gas and probability of mortality, compared to the static approach (because in the static approach the people are assumed not to escape and thus inhale more toxic gas as result of such behaviour). mZhang and Chen [40] have applied their dynamic approach to a hypothetical hydrogen sulfide releases from a gas gathering station and showed also that a dynamic modelling approach estimated a lower exposure to toxic gas compared to a static approach.

Besides these strengths of our study, we have to acknowledge several limitations. First, the response of the questionnaire was not optimal. In our study the response of 44% was similar to other DCE studies [25,41–43], but some selection bias may have occurred, although our respondents did not differ from non-respondents in age and gender. Young people in the study area often move to large cities elsewhere in the Netherlands for education or paid employment. Therefore, there are relatively more elderly people in the study area. Moreover, the distribution across educational levels in our study sample was similar to the general population of the Netherlands. Second, the DCE comprised a limited number of attributes. Having (too) many attributes would have increased the complexity of the study further, which might result in choice heuristics, in a lower participation, and an increase in choice inconsistency due to respondent fatigue [44]. In our application, the marine accident, we selected the most relevant attributes in our DCE, using literature (among others PADM) and a focus group study, but some relevant attributes may have gone unnoticed. For example, the DCE did not address an immediate escape behaviour prompted by visual and auditory perception because of the collision. Modelling with SeReMo showed that reaction time is important. In general, people only show protective behaviour when they are exposed to environmental cues (e.g. smells, smoke) [3,7]. Because it takes approximately 60–100 s before the cloud will reach the beach/quay, a large part of the people will not react immediately. Third, there may be a response bias whereby the decisions in accident scenarios evaluated by the DCE questionnaire differ from acute behavioural response in a real accident. According to Kahneman [45] in emergency situations it is more likely that people demonstrate a rapid and associative response than a rationale decision process that is slow and deductive. Despite that responders were encouraged to write down their first thoughts, it is possible that responders gave more (rational) thoughtful answers. Fourth, the parameters in the SeReMo (e.g. wind speed and direction) can have a significant influence on the predictions, i.e. changes in the dispersion direction and the spreading of the resulting toxic and combustible gases. Given the scenarios in our study, the assumption of a constant wind speed and weather stability class can be considered reasonable. Fifth, the reality is much more complex than the DCE and ReSeMo can predict. ReSeMo and the DCE are limited to a small number of protective action options. For example, in reality, bystanders may help each other and parents will try to get their children to safety. Nevertheless, we believe that the results of this study are sufficiently useful for safety managers.

Since there is limited experience with combining discrete choice experiments, that capture heterogeneity in behavioural choices, with accident models that predict causalities based on a scenario approach, it is recommended to apply this novel approach to a well-documented transport accident. Virtual Reality (VR) is becoming an established tool to investigate human behaviour in disasters [46]. This can improve our approach because VR is more realistic than a questionnaire.

To the best of our knowledge, there are no other studies that combine the results of a DCE investigation, that predicts protective behaviour of bystanders during an accident involving hazardous materials, with a dynamic approach for the impact of a toxic gas dispersion on casualties. Our study provides a new methodological framework how assumptions on protective behaviour in dynamic rescue models can be developed. The results of this dynamic risk assessment study can be used for developing interventions to diminish adverse health effects. For example, a short reaction time and escaping in cross-wind direction is of vital importance in most of the accident scenarios. Informing citizens about these preferred protective behaviours can be useful to improve the resilience of people. Alarm techniques such as sensors and SMS broadcasting (NL-alert in the Netherlands) can reduce the reaction time.

5. Conclusion

This study introduced an approach to estimate the influence of protective behaviour on expected injuries in transport accidents with hazardous materials. The main advantages of the approach is the use of CDE technique to investigate protective behaviour and the use of SeReMo dispersion model, incorporating protective behaviour, to calculate the number of causalities. It is a dynamic risk assessment approach that considers that people threatened by hazardous material are not 'stationary observers', but will exhibit protective behaviour. This approach will present a more realistic estimate of the number and severity of casualties in case of a large transport accident with hazardous materials.

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Author contributions

Arnold Bergstra: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. Inge Trijssenaar-Buhre: Conceptualization, Methodology, Software, Formal analysis, Visualization. Esther de Bekker-Grob: Conceptualization, Methodology, Software, Formal analysis, Visualization. Alex Burdorf: Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The Law for Protection of Personal Data prohibits the publication of data from this study. Interested researchers who meet the criteria for access to confidential data may request data access.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2022.103426.

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