

1 **A Review of Research on Driving Styles and Road**

2 **Safety**

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18 Abstract

19 **Objective:** To outline a conceptual framework for understanding driving style and, based on
20 this, review the state-of-the-art research on driving styles in relation to road safety.

21 **Background:** Previous research has indicated a relationship between the driving styles
22 adopted by drivers and their crash involvement. However, a comprehensive literature review of
23 driving style research is lacking.

24 **Method:** A systematic literature search was conducted, including empirical, theoretical and
25 methodological research on driving styles related to road safety.

26 **Results:** A conceptual framework was proposed where driving styles are viewed in terms of
27 driving habits established as a result of individual dispositions as well as social norms and cultural
28 values. Moreover, a general scheme for categorising and operationalizing driving styles was
29 suggested. On this basis, existing literature on driving styles and indicators was reviewed. Links
30 between driving styles and road safety were identified and individual and socio-cultural factors
31 influencing driving style were reviewed.

32 **Conclusion:** Existing studies have addressed a wide variety of driving styles, and there is an
33 acute need for a unifying conceptual framework in order to synthesise these results and make
34 useful generalisations. There is a considerable potential for increasing road safety by means of
35 behaviour modification. Naturalistic driving observations represent particularly promising
36 approaches to future research on driving styles.

37 **Application:** Knowledge about driving styles can be applied in programmes for modifying
38 driver behaviour and in the context of usage-based insurance. It may also be used as a means for
39 driver identification and for the development of driver assistance systems.

40

41 **Keywords:** driver profiling, driving pattern, driving habit, driver behaviour

42

43 **Précis:** Previous research on driving styles and road safety is reviewed based on a proposed
44 conceptual framework. Definitions, categorisation, investigation methods, influencing factors,
45 and applications are emphasised. Understanding the complexity and multidimensionality of
46 driving styles is important for implementation of adequate technological, organisational and
47 behavioural measures to reinforce safe driving styles.

48 **Introduction**

49 The concept of individual differences between drivers regarding crash involvement
50 probability, and possible explanations in terms of behaviour and background factors, dates back
51 to the old ideas of “accident proneness” as a general characteristic predisposing a person for
52 involvement in all types of accidents. This idea first appeared as an explanation for industrial
53 accidents, but was later also applied to road accident involvement (for an overview and references
54 regarding accident proneness, see Shinar, 2007, pp. 342-343).

55 Although “accident proneness” as a general predisposition for involvement in all types of
56 accidents has been discarded (Shinar, 2007), there seems to be clear evidence from road safety
57 research that drivers differ in crash involvement risk, and that these differences tend to be
58 relatively stable over time (see. e.g. Häkkinen, 1958).

59 The earliest research on individual differences in crash risk focussed on driver background
60 factors (e.g. personality, socioeconomic background, etc.). For example, Tillmann & Hobbs
61 (1949) carried out detailed interviews with crash-involved and crash-free taxi drivers and found
62 significant differences in their background. Part of the interviews with taxi drivers took place
63 during taxi trips, providing observational data for qualitative descriptions of “driving habits”. The
64 driving habits of taxi drivers with a high accident frequency were described as follows:

65 As a group they were easily distracted while driving. They tended to be readily annoyed at
66 other motorists on the road, often criticising their own driving mistakes in others. Horn
67 honking and racing other cars away from a stop light were their specialties (Tillmann and
68 Hobbs, 1949, p. 325).

69 The taxi drivers with low accident frequency on the other hand were described in the
70 following way:

71 These men were serious when driving and often refused to talk. They tended to be courteous
72 to other drivers on the road and stated that they were conscious of the fact that the other

73 driver might do the wrong thing. They appreciated the possible limitations of their vehicle
74 (Tillmann and Hobbs, 1949, p. 326).

75 In a second study, they compared a group of 96 crash-involved drivers from the general
76 population with a control group of 100 crash-free drivers and found clearly significant differences
77 in registered previous contacts with juvenile and adult courts, public health agencies, and social
78 service agencies handling family-related problems. One of their conclusions was the well-known
79 saying that “a man drives as he lives” (Tillman and Hobbes, 1949, p. 329).

80 Apart from such rather cursory observations, the early studies of individual differences in
81 crash involvement did not include actual measurements of driving behaviour, but it was more an
82 implicit assumption that the relationship between social background and personality on the one
83 hand and crash involvement on the other was mediated by differences in ways of driving.

84 One of the earliest quantitative studies of individual differences including behaviour
85 measurements was done by Weiss and Lauer (1930). They made a list of 44 different driving
86 behaviours supposed to be relevant indicators of the quality of driving, e.g., “application of
87 brakes”, “coasting downhill”, “use of rearview mirror”, “fail to signal”, etc. In-vehicle observers
88 then rated individual drivers on a scale from 1 to 5 on each behaviour item. However, these
89 authors did not present any results relating the behaviour scores to more objective safety
90 indicators like crash involvement. In the 1950’s some studies correlated rating scales and driving
91 habit checklists with accident involvement (see Häkkinen, 1958, p. 77). There was also a series of
92 studies of driving habits by Lewis (1951, 1953, 1956), using in-vehicle camera observations of a
93 small group of drivers. The results suggested that “safe drivers drive more constantly in the same
94 manner when the same driving situations are repeated” (Häkkinen, 1958, p. 78).

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98 Table 1: Data collection methods to study driving styles.
99

	Method	Sample references
Self-report instruments	Driving Style Questionnaire DSQ*	West et al., 1990; French et al., 1993
	Driving Style Questionnaire*	Ishibashi et al., 2007
	Driving Behaviour Questionnaire DBQ	Reason et al., 1990; Parker et al., 1995
	Multidimensional Driving Style Inventory MDSI	Taubman-Ben-Ari et al., 2004
	Driver Vengeance Questionnaire	Wiesenthal et al., 2000
	Driving Anger Scale DAS	Deffenbacher et al., 1994
	Driving Anger Expression Inventory DAI	Deffenbacher et al., 2002
	Driver Aggression Indicators Scale DAIS	Sümer et al., 2006
	Propensity towards Angry Driving PAD	Dahlen and Ragan, 2004
	Dula Dangerous Driving Index DDDI	Dula and Ballard, 2003
Driving Behaviour Inventory DBI**	Gulian et al., 1989	
Behaviour recording	Observation by in-vehicle observer	Tillman and Hobbs, 1949; West et al., 1993; Bukasa & Risser, 1985; Amado et al., 2014
	Site-based traffic observation	Keskinen et al., 1998; Aronsson, 2006
	Simulator study	Ungoren and Peng, 2005; Desai and Haque, 2006; Yan et al., 2007; de Waard et al., 2009; Farah et al., 2009; Richer and Bergeron, 2009; Cho et al., 2006; Xiong et al., 2012; Chen et al., 2013
	Controlled field study with instrumented vehicle	Miyajima et al., 2007; Takeda et al., 2011; Paefgen et al., 2012
	Naturalistic driving observation	Paefgen et al. 2012; Johnson and Trivedi, 2011; Eren et al., 2012; Hong et al., 2014; af Wählberg, 2006; Bagdadi and Várhelyi, 2011; Reagan et al., 2013; Knippling et al., 2004

100 * There are two quite different instruments with the name Driving Style Questionnaire. We will use the
101 acronym DSQ only for the West et al. (1990) questionnaire.

102 ** The DBI was developed in order to study *driver stress*. It is listed here because it includes some behavioural
103 items closely related to driving style, such as “When irritated I drive aggressively”, and because it is used
104 extensively in research on driving styles.

105

106 The seven decades that have passed since those first attempts of systematic and scientific
107 observations of differences in driving habits (or driving styles) have witnessed a tremendous
108 development in this field of research. Although it is generally assumed that driving styles are

109 related to crash risk, there are still several unresolved issues regarding the details of this
110 relationship, and how safe versus unsafe driving styles should best be modelled and measured.
111 However, perhaps most importantly, there is still a lack of a common underlying conceptual
112 framework to guide this research and clearly distinguish the concept of driving style from other
113 constructs such as driver state, driver condition, and driver behaviour in general.

114 Research on driving styles has used both self-report methods and observation of actual
115 behaviour. Self-report instruments have mostly been developed with the explicit aim of
116 measuring driving styles, whereas direct observation of driving styles uses more or less the same
117 methods as in research on driving behaviour in general. Table 1 shows an overview with
118 examples of both self-report and behaviour observation/recording methods. It should be noted
119 that several of the studies reviewed here have used a combination of self-report and observation
120 methods.

121 In this paper, we first discuss key terms and definitions commonly used in this research area
122 and suggest a general definition of driving style. We then outline a framework for conceptualising
123 driving style and a scheme for categorisation and operationalization in terms of global and
124 specific driving styles. On this basis, we review the literature on 1) global and specific driving
125 styles, 2) the relation between self-reported and observational measures of driving styles, 3) the
126 association between driving style and road safety, 4) background factors that influence driving
127 styles and 5) potential applications of driving style research, in particular techniques for
128 modifying driving style. We conclude with a summary of the main findings and some suggestions
129 for future directions of driving style research.

130

131 **Inclusion criteria for review**

132 Candidate material was gathered by a systematic search on IEEE Xplore, and ISI Web of
133 Science, with search terms “driving style” and “safety”; this gave about 90 hits. This set was

134 supplemented by literature previously known by the authors, as well as from informal search on
135 Google Scholar, yielding a total set of about 160 literature items (articles, books, reports).

136 Literature items were considered relevant if they focused on either 1) driving styles related to
137 road safety, 2) driving behaviour relevant to research on driving style and road safety, 3)
138 methodologies to study and/or infer driving styles, or 4) factors shown or assumed to influence
139 driving styles. A further selection of papers to consider for review was made based on a
140 preliminary definition of driving style as pertaining to differences in driving behaviour between
141 drivers or groups of drivers (the issue of defining driving style will be further discussed below).
142 This means that research focusing on differences between driving situations rather than between
143 drivers was excluded. Only literature explicitly addressing some indicator(s) or measure(s) of
144 driving style, or some specific example of a driving style, was included in this review, hence
145 literature mentioning driving style as an unspecified concept was excluded. Based on these
146 criteria, a total of about 100 literature items related to driving styles were reviewed. About one
147 half of the items had the words “driving style” in the title or abstract.

148 To make this review manageable, the literature on driving styles or driving behaviours not
149 related to road safety (e.g., related to fuel economy and environmentally friendly driving) are not
150 covered here but are addressed in, for example, Ericsson (2000), Savaresi et al. (2010), and
151 Rafael et al. (2006).

152

153 **Defining driving style**

154 Definitions of driving style found in the reviewed literature are given in Table 2. The definition
155 by Lajunen and Özkan (2011) is very much in accordance with the definition by Elander et al.
156 (1993). The definition by Murphey et al (2009) differs considerably from most other definitions,
157 in being almost equivalent to driving behaviour in general, and thus this definition is probably too

158 general to be very useful. Other definitions tend to emphasise decision-making (Deery, 1999) and
 159 ways of thinking (Ishibashi et al. 2007) rather than observable behaviour.

160 *Table 2. Existing definitions of driving style*

Definition	Reference
“Driving style concerns individual driving habits – that is, the way a driver chooses to drive”	Lajunen and Özkan (2011)
“Driving style concerns the way individuals choose to drive, or driving habits that have become established over a period of years”	Elander et al. (1993)
“An attitude, orientation and a way of thinking for daily driving”	Ishibashi et al. (2007)
“Driving style is concerned with decision making aspects of driving, that is, the manner in which people choose to drive or driving habits that have developed over time”	Deery (1999)
“Driving style is defined as a set of activities and steps that an operator uses when driving an engine powered vehicle, according to his personal judgment, experience and skills”	Rafael et al. (2006)
“Driving style is the way in which a driver chooses to drive and is governed by a combination of social, neurobehavioral, and biological mechanisms”	de Groot et al. (2012)
“Driving style is described as a relatively stable characteristic of the driver, which typifies his/her personal way of driving, the way he/she chooses to drive”	Saad (2004)
“Dynamic behaviour of a driver on the road”	Murphey et al. (2009)
“One’s preferred way of driving that, over time, develops into driving habits”	Kleisen (2011)

161

162 Despite the differences, there seem to be some aspects that most definitions have in common,
 163 which we can summarise in the following three conditions defining the concept of driving style.
 164 First, driving styles differ across individuals or between groups of individuals. Second, a driving
 165 style is a habitual way of driving, which means that it represents a relatively stable aspect of
 166 driving behaviour. Third, most definitions in Table 2 imply that driving styles reflect conscious
 167 choices made by the driver. We will endorse the first two conditions. However, we will question
 168 the usefulness of implying that the driver deliberately chooses his/her driving style. Thus, we
 169 include both consciously chosen ways of driving and subconscious automatised behaviour in our
 170 definition, as long as the behaviour is habitual and relatively permanent. In Lajunen and Özkan’s
 171 (2011) definition, driving *skills* and driving style represent two complementary and independent
 172 pathways to crash risk. We will suggest a link from driving skills to driving style, implying that a
 173 person’s driving style is partly a function of his/her driving skills, in addition to the conscious

174 choices made during driving. Some definitions include the additional criterion that driving styles
175 “become established over a period of years” (Elander et al. (1993) or “have developed over time”
176 (Deery, 1999). We do not think this is a necessary criterion, since it seems to exclude the
177 existence of driving styles among novice drivers.

178 Here we make an attempt to capture most of the common elements in previous definitions in
179 an effort to have a clear and applicable definition for future work in this field and also to
180 distinguish between driving styles and the wider concept of driving behaviour. Therefore, we
181 define a driving style as a “habitual way of driving, which is characteristic for a driver or a group
182 of drivers”. By ‘habitual way of driving’ we mean driving behaviour that tends to occur in a
183 consistent way across driving occasions for a given driver, and may include both automatised
184 skills and more consciously controlled behaviour. The concept of a driving habit is further
185 elaborated in the following section. ‘Driving’ here refers broadly to all behaviours performed by
186 the driver related to the goal of travelling from a point A to point B, including basic vehicle
187 control, tactical decisions as well as strategic decisions related, for example, to route choice and
188 seat belt use. *Driving habit* is commonly used interchangeably with driving style (e.g., in the first
189 two definitions mentioned above). It should be noted though, that Kleisen (2011) distinguishes
190 between driving style and driving habit and defines driving style as “one’s preferred way of
191 driving that, over time, develops into driving habits” (p. 156). As pointed out above, our view is
192 that both consciously preferred action and automatised habits may be defined as driving styles.
193 Furthermore, our definition entails the possibility that an individual driver may have a repertoire
194 of driving styles applied under different conditions, for example in a specific driving
195 environment.

196 It is necessary to clarify the distinction between driving style and driving behaviour in general.
197 The concept of driving behaviour includes all actions (both overt acts and covert or mental
198 operations) a driver performs during driving. Driving styles are subcategories of driving
199 behaviour, satisfying the criterion of varying systematically between individual drivers or groups

200 of drivers, and also being habitual, as implied by the definition above. Driving behaviour varies
201 systematically also across different road, traffic and driving conditions, such as traffic density,
202 road geometry, weather, light conditions etc. Drivers may show different patterns of behaviour in
203 different conditions. We have chosen to exclude behaviour patterns that are exclusively
204 determined by the driving context from our definition of driving style.

205

206 **A conceptual framework for understanding driving** 207 **style**

208 As we have shown in the previous section, the concept of driving style has been hard to pin
209 down and the term has been used in a variety of different meanings. Thus, in order to structure
210 the present review, there is a need for a more precise conceptualization of the driving style
211 construct. We have not found any research literature explicitly discussing habit formation as
212 applied to the development of driving styles. Although it is beyond the scope of this review to
213 present a complete theory or model for the development of driving styles, we will present a
214 tentative framework here. The framework is based mainly on the concept of reinforcement, and
215 the assumption that the reinforcement conditions during driving are constituted by a wide variety
216 of individual, social, cultural, environmental and technological factors.

217 This section thus expands on the general definition we proposed with the aim to outline a
218 tentative framework for understanding driving style. In the previous section, we proposed to
219 define driving style as a “habitual way of driving, which is characteristic for a driver or a group of
220 drivers”. Thus, the core idea in this definition is the link between driving style and habit. In order
221 to make this idea explicit, the concept of a driving habit needs to be further elaborated.

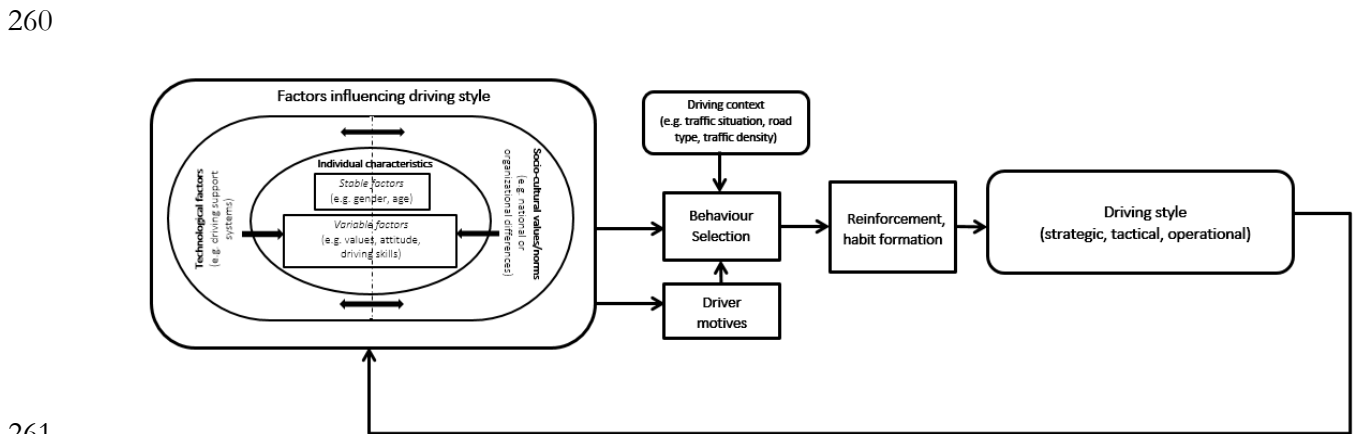
222 The general idea proposed here is that driving habits are formed partly as a result of individual
223 driver characteristics, partly by social and cultural values and partly by existing technology.
224 Individual characteristics include driving skills as well as dispositions towards certain behaviours
225 related to personality characteristics (e.g., sensation seeking, risk taking) which could be partly

226 biologically determined. Socio-cultural values refer to the norms regarding preferred or
227 acceptable driving behaviour that prevail in the driver's local social context (e.g. family, friends,
228 and employer) as well as on the national/regional level. Technological factors include, for
229 example, the way the vehicle is constructed (e.g., the steering and braking dynamics) as well as
230 on-board systems that alert the driver on potential hazards and/or automate part of the driving
231 task.

232 We further suggest that certain driving behaviours develop into habits by a process of
233 *reinforcement*. There may be different reasons why a certain driving behaviour occurs in the first
234 place. On the one hand, it may be related to certain *motives*, including the general motive to arrive
235 at the destination as well as more specific *extra motives* (Näätänen and Summala, 1976) which may
236 be more or less related to the goal of accomplishing the trip. These may include expediency (e.g.,
237 arrive at the destination as fast as possible), aggression (e.g., a desire for retaliation if offended by
238 another road user), compliance to behavioural norms (e.g., keeping up with the traffic pace),
239 proving oneself to peers or seeking the thrill of speeding. Extra motives may also include the
240 desire to perform secondary, non-driving related tasks, such as texting or talking on the cell
241 phone while driving. As suggested by Näätänen and Summala (1976), such *excitatory motives* are
242 balanced by *inhibitory motives* which serve to hold back certain behaviours associated with too high
243 costs, related for example to the perceived risk of crashing, receiving a speed ticket or violating
244 socially accepted norms.

245 Alternatively, the driver may engage in some behaviour more or less by coincidence, without
246 necessarily making a conscious decision. Such behaviours may be the result of intuitive
247 conceptions of how to behave while driving, and it may also be influenced by the driver's skills
248 and knowledge. In addition, behaviour selection is influenced by technological factors. For
249 example, engagement of an Adaptive Cruise Control function may be regarded a behaviour in
250 itself which has a strong impact on longitudinal vehicle control. Furthermore, behaviour selection
251 is strongly determined by the current driving situation which creates opportunities or constraints

252 for action. For example, a driver strongly motivated to send a text message may be more inclined
 253 to do so while driving on a sparsely trafficked motorway than in busy city driving; a desire to
 254 overtake may only be put into action if the driver judges that overtaking is possible given the
 255 present traffic situation. Irrespective of its origin, we suggest that a behaviour may become
 256 reinforced and develop into a habit, if it consistently results in positive outcomes. The term
 257 ‘driving style’ thus refers to those driver behaviours that have developed into driving habits and
 258 hence recur reliably within and between trips. The proposed framework is summarised in Figure
 259 1.



261
 262 *Figure 1: A tentative model of the establishment of driving style in terms of a process of habit formation*
 263

264 Finally, it should be noted that driving styles may belong to all levels in the well-known
 265 hierarchical tri-level model of driving behaviour, distinguishing between behaviour at the *strategic*,
 266 *tactical*, and *operational* levels (Michon, 1985). Driving styles at the operational level include steering
 267 or acceleration habits. Driving styles at the tactical level include, for example, the habitual choice
 268 of speed and headway, while examples of driving styles at the strategic level include habitual route
 269 choice and seat belt use. A similar tri-level classification, with particular reference to driver
 270 information needs, was previously formulated by Allen et al. (1971), in terms of *navigation* (macro-
 271 performance), *guidance* (situational performance), and *control* (micro-performance).

272

273 **Categorisation and operationalization of driving style**

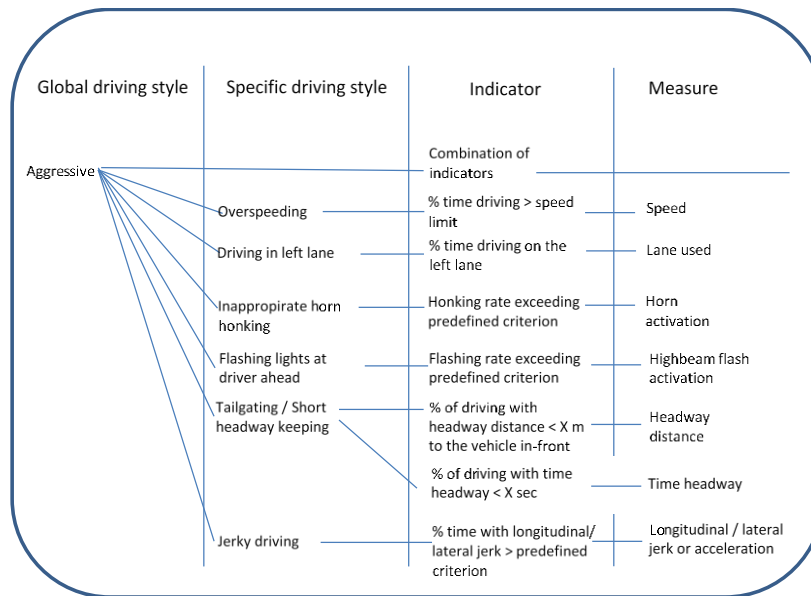
274 In the research literature, driving styles are operationalized at different levels of specification,
275 from single indicators like speeding or hard acceleration to very general concepts like e.g.
276 “aggressive driving” or “risky driving”, which may be based on a combination of several more
277 specific behavioural indicators. For classification of driving styles we therefore suggest a
278 distinction between *global* and *specific* driving styles. Based on the framework we propose, one
279 potentially useful way to conceptualise global driving styles is in terms of their underlying
280 motives. Thus, for example, aggressive driving may be manifested in a variety of different
281 behaviours such as frequent honking, tailgating, gesturing etc. These behaviours could all possibly
282 be related to the same underlying excitatory motive of punishing other road users for a perceived
283 offence. A specific driving style refers to a specific habitual behaviour, such as speeding. Thus, a
284 global driving style generally constitutes a set of specific driving styles. The operationalization of
285 a driving style (i.e., the specification of how it is measured) is here called an *indicator*.

286 Thus, a global driving style is generally operationally defined on the basis of several indicators,
287 whereas a specific driving style is defined by a single, or a few, indicators. Since the number of
288 indicators may vary from one to several, it is more appropriate to consider the global vs. specific
289 more as a continuum than as a dichotomy. Finally, the term *measure* refers to the basic signals that
290 are used as input for the calculation of indicators. This scheme is illustrated in Figure 2.

291 Based on this general classification scheme, and the conceptual framework outlined above, the
292 remainder of this section reviews and discusses some common global and specific driving style
293 categories found in the literature.

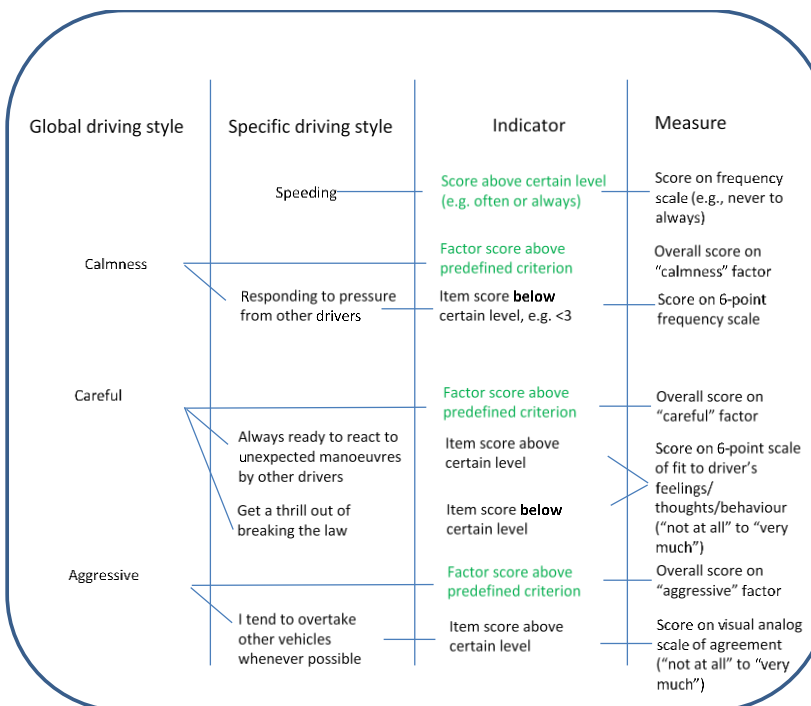
294

295 **Examples from data collected through driving observations (simulator/field**
 296 **operational test (FOT)/naturalistic driving study)**



297

298 **Examples from data collected through questionnaires**



299

300 *Figure 2: Examples illustrating relationships between driving styles, indicators, and measures. The examples are based on the*
 301 *reviewed literature (see text for references).*

302 Concerning *global* driving styles, *aggressive driving* is a very common term used both in research
303 literature (e.g. Shinar, 2007) and in popular publications to describe what is considered typical
304 maladaptive and risk-related behaviour in traffic, and it is probably the single driving style
305 concept that has received most attention in road safety research. For a general discussion about
306 this concept, we refer to Shinar (2007, Chapter 9) and Persak (2011). Shinar (2007) distinguishes
307 between “hostile aggression” and “instrumental aggression”. The former category comprises
308 hostile reactions directed towards other road users, which serve no mobility purpose, such as
309 verbal abuse, physical attack, or hand gestures. The terms “road rage” (see Shinar 2007), “driving
310 vengeance” (Wiesenthal et al., 2000), and angry driving (e.g. Dahlen and Ragan, 2004) seem to
311 refer to this aspect of aggressive driving. By contrast, instrumental aggression comprises
312 behaviours with the intention to reach the goal faster, such as weaving, tailgating, speeding, or
313 running red lights. Thus, honking may be either hostile, if done to “disapprove” of other road
314 users’ behaviour after an action, or instrumental if carried out to influence other road users to do
315 something (for example, honking at a driver who is late to start when a traffic light turns green).
316 Based on the proposed framework, these two forms of aggressive driving reflect different
317 underlying motives (retaliation and expediency respectively) although their constituent sets of
318 specific driving styles partly overlap. Instrumental aggression seems strongly related to the
319 concept of “impatience in driving”, one of the factors of the Ishibashi et al. (2007) Driving Style
320 Questionnaire, which also reflects motives related to expediency.

321 Aggressive driving has mainly been studied based on self-report instruments. Some
322 questionnaires were designed explicitly for measuring driving aggression in general (e.g. Sümer et
323 al., 2006) or hostile aggression in particular, such as “driving vengeance” (Wiesenthal et al., 2000)
324 or “driving anger” (Deffenbacher, 1994; 2002). In addition, some of the general self-report
325 measures of driving styles contain driving aggression as one of several factors, often based on
326 factor analysis of a large number of questionnaire items. For example, “angry driving” is one of
327 the eight driving styles measured by the Multidimensional Driving Style Inventory (MDSI) by

328 Taubman-Ben-Ari et al. (2004), and “aggressive driving” is a subscale of the Dula Dangerous
329 Driving Inventory (Dula and Ballard, 2003). Driving aggression is also one of the factors of the
330 Driver Behaviour Inventory DBI (Gulian et al., 1989), measured e.g. by the item “When irritated,
331 I drive aggressively”. Furthermore, “aggressive violations” is one of the commonly described
332 factors of the Driving Behaviour Questionnaire DBQ (Reason et al., 1990; Parker et al., 1995). It
333 seems like most of these terms refer mainly to the “hostile” variety of aggressive driving
334 discussed above.

335 *Deviant and risky driving.* Although there is probably a high correlation and overlap between
336 aggressive driving styles and other types of risky or deviant driving styles, it is possible to drive in
337 a risky manner without necessarily being aggressive (in the “hostile” sense). Various concepts in
338 the driving style research literature refer to such behaviour. The MDSI (Taubman-Ben-Ari et al.,
339 2004) contains a factor named “risky driving style”, and the same term is also used by Richer and
340 Bergeron (2009) and by Dula and Ballard (2003). Other related terms found in the research
341 literature include “reckless and careless” driving style (Ishibashi et al., 2007), and dangerous
342 driving (Knipling et al., 2004).

343 Some studies refer to the deviance aspect of driving as a characteristic of risky driving styles.
344 Batoool et al. (2012), in a discussion of road safety in Pakistan, used the term “deviant driving
345 styles” as a generic concept, and Sakaguchi (2003) talks about “unusual behaviour” as a common
346 term to describe his findings for a series of more specific driving style indicators. “Deviance” is
347 also one of the six factors of the French et al. (1993) Driving Style Questionnaire DSQ, measured
348 by items like “Do you overtake on the inside?” or “Do you ever drive through a red traffic
349 light?”. In terms of our framework, the deviance concept may be interpreted as referring to a
350 situation where driving habits deviate from socially accepted norms.

351 *Defensive driving.* Although the focus in driving style research tends to be on the negative and
352 risk-related driving styles, it is also important to consider the opposite end of the risky-safe
353 continuum. An example of a common term to denote a positive driving style is *defensive driving*,

354 which has been studied particularly in the context of driver training (e.g., O'Day, 1970;
355 Lähdeniemi, 1995). In relation to environmentally friendly driving, defensive driving is often
356 conceptualised as the contrast to aggressive driving (see e.g. Tzirakis and Zannikos, 2007).

357 *Concentrated and focused driving.* Some studies have focused on driving styles as related to
358 concentration and attention to the driving task. The DSQ by French et al. (1993) contains a
359 factor which the authors named “focus”, measured primarily by items like “Do you find it easy to
360 ignore distractions?” and “Do you ignore passengers?”. A similar factor of the Gulian et al.
361 (1989) Driver Behaviour Inventory DBI is “driving alertness”. According to our framework, this
362 can be related to motives for engaging in secondary (distracting) tasks. It may be suggested that
363 the strength of these motives are to a large extent determined by the emotional value of the
364 secondary task to the driver (Engström, Victor and Markkula, 2013). For example, a driver who
365 has developed an “addiction” to texting/social media would be expected to be more inclined to
366 habitually take the eyes off the road in order to interact with a smartphone than a driver who
367 seldom texts or uses social media.

368 As shown by the review so far, it is clear that there are many different terms that have been
369 used to label global driving styles but little consensus on their precise meaning. In general, these
370 terms and concepts seem to derive from everyday language and seem to have been coined more
371 or less independently by each author, often in the context of the development of a self-report
372 instrument. As a result, the terms used (such as aggressive, risky, reckless, deviant, defensive or
373 focused driving) seem to represent somewhat different concepts which are difficult to reconcile
374 and generalise. At the most general level, one may distinguish between aggressive/risky and
375 defensive/careful/focused driving styles, where the former refers to habitual driving behaviour
376 dominated by excitatory motives (focusing on accomplishing goals) while defensive driving
377 would refer to habitual behaviour dominated by inhibitory motives (focusing on avoiding risk).

378 A key advantage of conceptualising global driving styles based on underlying motives is that it
379 is precisely these motives that need to be targeted in order to modify an unsafe driving style (as

380 further discussed below). However, a possible disadvantage is that this scheme does not seem to
381 account for driving styles that do not originate from specific motives. Thus while most global
382 driving styles addressed in the literature reviewed here seem to be associated with driver motives,
383 potential alternative classification criteria may also be considered.

384 It could also be noted that some of the self-report scales contain a mixture of ‘true’ driving
385 styles, referring to habitual behaviours, and more subjective states or conditions, which should
386 rather be classified as background factors than as driving styles (we discuss the relationship
387 between driving styles and background factors in a subsequent section). For example, in the
388 Ishibashi et al. (2007) Driving Style Questionnaire, some factors rather reflect self-rated driving
389 skills (*Confidence in driving skills*), attitudes and values (*Importance of automobile for self-expression*), or
390 emotional states or dispositions (*Anxiety about traffic accidents*). Similarly, in the MDSI (Taubman-
391 Ben-Ari et al., 2004) some of the factors do not count as driving styles by our definition, for
392 example, the *anxious* and *distress-reduction* categories are questionable, since they refer to emotional
393 states rather than to driving behaviour. This broad definition of driving style behaviours seems to
394 be intended by the authors, since participants were asked to rate the items not only in relation to
395 their behaviour, but also to their feelings and thoughts.

396 *Specific driving styles* refer to specific habitual, consistently recurring, behaviours and can be
397 grouped into the following common categories: ‘longitudinal control’, ‘lateral control’, ‘gap
398 acceptance’, ‘visual behaviour’, ‘errors and violations’, and ‘other’. Examples of driving styles and
399 measures within each of the categories are shown in Table 3, and some of the examples are
400 further elaborated in the following text. It should be emphasised that the driving behaviours
401 listed under the “driving styles” column in Table 3, are considered driving styles only if they
402 occur in a consistent manner across driving occasions, as implied by our definition. When
403 occurring occasionally, they are considered as driving behaviour only.

404

405

Table 3. Examples of specific driving styles and related measures, grouped in categories, with references.

Cate- gories	Driving styles	Measures	References
Longitudinal control	Speeding and/or hard braking/acceleration	Speed Acceleration	Paefgen et al., 2012; Aljaafreh et al., 2012; Eren et al., 2012, Johnson and Trivedi, 2011; Elander et al., 1993; af Wählberg, 2006; Robertson et al., 1992; Sümer et al., 2006; de Waard et al., 2009; Keskinen et al., 1998; Persak, 2011; Ericsson, 2000; Quenault, 1967
	Jerky driving	Jerk	Murphey et al., 2009; Bagdadi and Várhelyi, 2011; Desai and Haque, 2006
	Tailgating	Time headway Distance headway	MacAdam et al., 1998; Cho et al., 2006; Miyajima, 2011; Xiong et al., 2012; Underwood, 2013
Lateral control	Left-lane preference	Lane choice	Reimer et al., 2013
	Variable lateral position	Steering angle Lateral position	Ungoren and Peng, 2005; Cho et al., 2006; Yan et al., 2007; Underwood, 2013
	Speeding in curves	Lateral acceleration	Robertson et al., 1992; Reymond et al., 2001; Lajunen et al., 1997, Aljaafreh et al., 2012
Gap ac- ceptance	Late crossing	Time between vehicles at crossings	Keskinen et al., 1998; Yan et al., 2007
	Frequent overtaking	Passing gap when overtaking	Farah et al., 2009
Visual behaviour	Fixating close to own vehicle	Area of fixation	Mourant and Rockwell, 1970;1972
	Frequent long looks away from road	Direction of looking/ Eyes-off-path time Fixation length and frequency	Serafin, 1994; Underwood et al., 2002; 2003; Crundall and Underwood, 2011
	Failure to look in side mirror during lane change	Mirror checking	Quenault, 1967; Crundall and Underwood, 2011
Errors and violations	High frequency of respective actions	Failing to use indicator	Quenault, 1967; Reason et al., 1990
		Drive through red traffic light	
		Violate stop sign	
		Use wrong gear	
Other	High frequency of respective actions	Unusual manoeuvres	Quenault, 1967; Shinar, 2007
		Near accidents Inappropriate honking Making gestures to other road users	
	Leaning on steering wheel	Driving posture	

407 Concerning *longitudinal control*, *speed* and its derivative *acceleration* seem to be the most frequently
408 used measures of driving styles. Although risky driving styles are mostly associated with *high*
409 speeds, there are some indications that even *lower* than normal speeds may be risky. For example,
410 de Waard et al. (2009) investigated merging speeds for drivers on a motorway entrance ramp, on
411 the assumption that merging at a lower speed could make the manoeuvre more risky. Habitual
412 speeding may be related to a range of excitatory motives such as expediency, social group
413 pressure, and hedonistic motives such as seeking the thrill of speeding or conforming to group
414 norms (e.g., following the pace of traffic even if it is above the legal speed limit). Failure to keep
415 speed posted limits may also be due to inattentive driving, for example when failing to notice a
416 temporary shift in speed limit due to not paying sufficient attention. Unusually low speeds may
417 be related to inhibitory motives (e.g., risk aversion), which may be most common among older
418 drivers.

419 *Jerky driving*, defined as a driver's speed of accelerating or decelerating (i.e., jerk profile), was
420 used by Murphey et al. (2009) as an indicator of individual driving styles. Bagdadi and Várhelyi
421 (2011) found that the jerk at the beginning and end of a braking manoeuvre was the best
422 jerkiness indicator of safety-critical driving behaviour.

423 A different approach to jerkiness was taken by Desai and Haque (2006), who introduced the
424 concept of "spikiness index", based on the jerk profile. They hypothesised that this index can be
425 used both as an indicator of alertness and as a signature of individual driving styles.

426 Robertson et al. (1992) equipped a vehicle with a dual-axis accelerometer in order to
427 investigate "acceleration signatures" for a sample of 10 drivers during driving through a
428 predefined route. The acceleration signatures were based on combined registration of lateral and
429 longitudinal accelerations. The same measure has subsequently been used in another driving style
430 study by Lajunen et al. (1997). Like speed, these types of jerky driving indicators are quite
431 unspecific with respect to the motives underlying the behaviour and could reflect aggressive
432 driving as well as hurried/impatient or inattentive driving. However, it could also reflect an

433 individual automatised control strategy that developed more or less independently of specific
434 motives.

435 Based on *headway* measurements, MacAdam et al. (1998) formulated a “driving aggressivity
436 index” based on the relative prevalence of the behaviour categories “closing in rapidly”, “closing
437 in”, and “following”, as opposed to “falling behind” of “falling behind rapidly”. Similarly,
438 Fancher et al. (1998) considered drivers as either flow conformist, extremist, hunter/tailgater,
439 planner or ultraconservative, based on measurements of headway and closing speed in an
440 intelligent cruise control field operational test. These types of indicators seem to be somewhat
441 more specific than speed and jerkiness, and extreme tailgating appears like a strong indicator
442 reflecting hostile aggressiveness and/or impatient driving. The habitual adoption of a
443 comfortable headway during normal driving is also influenced by the socially accepted norm in a
444 country or region. The choice of short headways could be partly explained by the presence of
445 excitatory motives (e.g. time pressure, social pressure).

446 Concerning *lateral control*, examples of driving styles related to steering and lane-keeping is
447 highly variable lateral position, or tendency to cut across the central lane marker on bends. The
448 former is indicative of inattentive driving, in particular visual distraction (Engström, Johansson
449 and Östlund, 2005), while the latter may rather reflect motives related to expediency. A driving
450 style related to *lane choice* is excessive or unnecessary driving in the left lane (which in most
451 countries with right-hand traffic is recommended or reserved for overtaking), indicated by e.g.
452 percentage of driving time in left lane. *Lateral acceleration* is a particularly interesting indicator,
453 since it reflects speed choice behaviour in curves, relative to the curve radius, which is a likely
454 indicator of crash risk, especially under low-friction conditions. It is one of the parameters
455 determining the “acceleration signature” developed by Robertson et al. (1992), described above.
456 Reymond et al. (2001) refer to previous studies showing that drivers adjust their speed in curves
457 so that maximum lateral acceleration is lower at high speed (i.e. in less sharp curves), and they
458 suggest that the relationship between curvature and maximum acceptable lateral acceleration can

459 differentiate between “normal” and “fast” driving styles. High values of lateral acceleration would
460 be expected to correlate with speeding and generally seems to be driven by similar driver motives
461 (i.e., expediency, social group pressure, thrill of speeding etc.).

462 *Gap acceptance* behaviour may refer, for example, to time gaps when entering a crossing traffic
463 stream, or *passing gap* to an opposing vehicle in an overtaking situation. Example of a driving style
464 based on this measure is accepting short time gaps when entering a main road. Short time gaps
465 seem to mainly reflect motives related to expediency.

466 Research on individual differences in *visual behaviour* has mainly focused on differences
467 between novice and experienced drivers in scanning patterns, based on eye movement
468 recordings. This field of research has been strongly influenced by the early studies by Mourant
469 and Rockwell (1970;1972), where a main finding was that novice drivers tended to concentrate
470 their visual search in the area just ahead of the vehicle, whereas more experienced drivers looked
471 farther ahead. Subsequently, eye fixation has been investigated in several studies of how both age
472 and experience influence the visual behaviour of drivers (Serafin, 1994; Underwood et al., 2002;
473 2003). For an overview of this research area, see for example Crundall and Underwood (2011).

474 It may be suggested that these indicators mainly reflect the development of increasingly
475 automatised and efficient visual scanning with increased experience (driven by the general
476 reinforcement process in Figure 1), with an increased tendency to focus scanning on areas where
477 the most relevant information is expected. By contrast, visual behaviour related to the
478 engagement in secondary tasks can be viewed as a direct indicator of inattentive driving. As
479 discussed above, this may be considered as a driving style to the extent distracted behaviour has
480 developed into a habit. As noted above, it may be predicted that the risk for habitual distraction
481 is greatest for drivers who developed an addiction to tasks such as texting or accessing social
482 media on a smartphone.

483 A wide range of specific driving *errors and violations* that are not included in the categories
484 discussed so far, have been used to define driving styles, mainly in self-report studies using the

485 DBQ (e.g., Reason et al., 1990) or similar instruments. Examples include driving through red
486 traffic lights, failure to use indicator signal, failure to stop before stop sign, using wrong gear, etc.
487 According to Reason et al. (1990) errors and violations are two distinct categories of unsafe acts.
488 Errors are defined as “the failure of planned actions to achieve their intended consequences”
489 (Reason et al., 1990, pp. 1315-1316), manifesting themselves either as *slips* and *lapses* (“the
490 unwitting deviation of action from intention”) or *mistakes* (“the departure of planned actions
491 from some satisfactory path towards a desired goal”). Violations on the other hand involve some
492 intention to commit the unsafe act. It should be noted, though, that some actions that are
493 violations in a legal sense may count as errors in a psychological sense, e.g., when a driver
494 unintentionally exceeds the speed limit or fails to observe a stop sign. Since errors and violation
495 thus have different psychological explanations, they may also need different types of
496 interventions.

497 Violations, such as intentionally running a red light, could generally be considered as due to
498 excitatory motives (e.g., time pressure, group pressure) that are sufficiently strong to override the
499 perceived risks related to committing the violation (e.g., losing one’s driving licence). To the
500 extent that such violations are committed systematically, the behaviour would qualify as a specific
501 driving style. By contrast, the commitment of errors does not generally seem to qualify as a
502 driving style unless they, for some reason, are not corrected and thus continue to be repeated.

503 *Other driving styles.* We assume that most specific driving styles listed in Table 3 may occur
504 either as isolated habits or together with other habits and thus being part of global driving styles.
505 For example, driving styles usually occurring as part of the global driving style hostile aggression,
506 such as making gestures to other road users, or inappropriate honking, can be considered specific
507 driving styles if they occur in isolation. We also assume that some specific driving styles, e.g.,
508 seating posture or hand position, may occur without any connection to any of the global driving
509 styles.

510 In addition to the driving styles discussed so far, future research may reveal additional
511 examples of stable patterns of driving behaviour that satisfy the definition of driving styles, both
512 global and specific. With the growing amount of behaviour observation data, *data mining* seems to
513 be a promising approach for this purpose, as well as for validating self-report driving style
514 indicators. For example, Constantinescu et al. (2010) used a data mining approach including
515 Hierarchical Cluster Analysis and Principal Components Analysis of several vehicle-based driving
516 parameters and identified four different driving styles, which they described as aggressivity,
517 speed, accelerating, and braking.

518

519 **Relationship between self-reported and observed** 520 **driving styles**

521 The ultimate indicators of a driving style are how a driver actually drives, and consequently the
522 “golden standard” for a driving style measurement is unobtrusive observation of driving
523 behaviour. It is therefore an interesting issue to what extent different scores on self-report
524 instruments are reflected in corresponding differences in observed driving styles.

525 West et al. (1993) investigated correlations between observations by in-vehicle observers and
526 self-reported driving styles using the Driving Style Questionnaire DSQ and found high
527 correlations for speed (Pearson correlations between 0.55 and 0.65) and also significant but
528 moderate correlations for calmness (0.39 – 0.41), attentiveness (0.29) and carefulness (0.38).

529 Amado et al. (2014) compared errors and violations assessed by in-vehicle expert observers
530 (through some observation forms) with participants’ self-reported errors. The authors reported
531 significant but low correlations between driver self-evaluations and some of the observed
532 violations and errors: speed errors ($r=0.24$), traffic light errors ($r=0.33$), brake and gear errors
533 (0.30), and clearance and checking errors ($r=0.18$). Overall, although some correlation was shown

534 between self-assessed and in-vehicle observer ratings, the participants generally over-estimated
535 their own driving competence.

536 Ishibashi et al. (2007) found significant correlations between some of the factors of their
537 Driving Style Questionnaire and observed driving style in a car-following study using an
538 instrumented vehicle. The highest correlations were found with gas and brake pedal operations
539 during deceleration. For example, “impatience in driving” was related to high brake pedal
540 operation ($r=0.50$) and close following ($r=0.66$).

541 Farah et al. (2009) found that the high scores on the Multidimensional Driving Style Inventory
542 MDSI “angry and hostile driving style” scale were significantly related to both higher speed
543 ($r=0.32$) and shorter passing gaps ($r=-0.20$). More recently, Helman and Reed (2015) reported
544 correlations ranging from 0.38 to 0.48 between the DBQ violations scale and driving speed
545 measured in a driving simulator.

546 It is well known that self-evaluations of behaviour may be biased, both in driving and in other
547 domains, e.g. by tendencies in the direction of socially desirable responses (Crowne and Marlowe,
548 1960; Lajunen et al., 1997). Despite such tendencies, the significant associations with objectively
549 measured behaviour reported here imply that self-report instruments can still play an important
550 role in driving style research.

551

552 **Are driving styles related to crash risk?**

553 A crucial issue regarding driving styles is the practical implications of the individual
554 differences. To what extent are driving styles related to crash risk, and which driving styles are the
555 most important predictors? For some driving styles involving notoriously risk-related behaviour
556 at a strategic level, like driving without using a seatbelt or driving under the influence of drugs or
557 alcohol, the relationship to crash involvement or injury risk is obvious. Other driving styles at the
558 strategic level, like route choice, may bear more subtle relationships to crash risk. The main issue

559 to be discussed here, however, is possible relationships between crash risk and driving styles at
560 the tactical or operational levels.

561 The study by Quenault (1967) compared observed driving styles of a group of drivers
562 convicted for traffic offenses with those of a control group, and found significant group
563 differences for the driving style measures mirror use, overtaking frequency, “unusual driving
564 behaviour”, and near accidents. This study did however not include any comparison between the
565 different driving styles regarding strength of association with crash involvement history.

566 Concerning crash involvement, several of the studies discussed here have compared driving
567 styles between groups of drivers with different crash involvement history. Although most studies
568 are correlational or based on qualitative assessments of driving styles, differences between crash-
569 involved and crash-free drivers may indicate causal relationships from driving styles to crash risk.
570 An example is the old study by Tillman and Hobbes (1949) where they found differences in
571 observed driving behaviour between taxi drivers with different crash records. Drivers with a high
572 accident frequency tended to be easily distracted while driving and to be readily annoyed at other
573 motorists on the road. As well, during the drive, they showed a disposition for horn honking and
574 racing other cars away from a stop light.

575 Some studies investigated correlations with self-reported crash involvement. For example,
576 West et al. (1990, 1993) found positive correlations between self-reported crash involvement in
577 the last 3 years and observed motorway speed (r ranging from 0.37 to 0.47 for different speed-
578 based indicators) in a sample of 48 drivers.

579 Using the Driving Style Questionnaire data from 711 drivers, French et al. (1993) showed that
580 the driving styles ‘speed’, ‘planning’ and ‘deviance’ (as defined by French et al., 1993) were all
581 significantly related to self-reported crash risk. However, a multiple regression analysis showed
582 that speed explained the effects of the other driving styles.

583 A review article by Elander et al. (1993) concluded that “with regard to driving style, faster
584 driving and deviant driving behaviour are consistently associated with more frequent crashes” (p.

585 290). In support of this conclusion they refer to among others the study of Wasielewski (1984)
586 showing that unobtrusively recorded driving speeds for a sample of 6 638 cars were significantly
587 related to state records of the driver's crashes.

588 af Wählberg (2006) compared various speed-related indicators regarding prediction of crash
589 involvement among bus drivers. Recording equipment was installed in a fleet of buses, and speed
590 and acceleration were recorded over a period of almost three years from about 250 drivers
591 observed on average during 3.2 trips. The author concluded tentatively that "celeration
592 behaviour" (an index based on acceleration and deceleration) was a better predictor of company-
593 recorded crash involvement than other speed-based indicators. However, the author points out
594 that this conclusion should be taken with great caution, because the difference between celeration
595 and other speed-based indicators regarding correlation with crash involvement was not
596 significant. Furthermore, there was a ceiling effect for maximum speed (speeds above 65 km/h
597 were not measured), which could have attenuated the correlation with crash involvement for this
598 variable. Using the same "celeration" index, Katsianis et al. (2013) found a significant correlation
599 ($r=0.39$) with self-reported crash risk, but this correlation was not significant (this study was
600 based on only 10 drivers). They did however find a significant correlation of 0.71 between "time
601 spent accelerating" (on an urban road) and self-reported crashes per distance driven.

602 There are also studies finding only low and insignificant correlations between driving style
603 measures and crash risk. For example, the original research with development and validation of
604 the Dula Dangerous Driving Index (Dula, 2003) showed insignificant correlations in the order of
605 $r=0.1$ with crash involvement, although there were significant correlations with self-reported
606 traffic tickets in the past two years.

607 Concerning the relationship between crash involvement and habitual errors or violations, de
608 Winter and Dodou (2010) did a meta-analysis of studies using the Driver Behaviour
609 Questionnaire (DBQ), and they found significant, but low correlations with self-reported crash
610 involvement both for errors and violations. The correlations were slightly higher for violations

611 than for errors. The predictive value of violations for crash involvement is further shown by
612 studies comparing criminal records between crash-involved and crash-free records. Junger et al.,
613 (2001) found that crash-involved drivers were about five times more likely to have a history of
614 driving-related violations, compared to drivers without crashes.

615 Turetschek (2006) reported an investigation by Bukasa and Risser (1985) of how behaviour
616 assessed through the “Wiener Fahrprobe” was related to individual accident records and to
617 accident types in 51 road sections along a standardised route. The results showed significant and
618 moderately high correlations between the accident records and some behaviour assessed by the
619 observers. The two highest positive correlations with previous crash involvement was found for
620 “exceeding speed limits” ($r=0.35$) and “too short distance to car ahead” ($r=0.33$), whereas
621 negative correlations (indicating a protective effect) were found for “speed not exceeding speed
622 limits and well adapted to situation” ($r=-0.40$) and “early deceleration whenever deceleration
623 becomes necessary” ($r=-0.24$).

624 The study by Bukasa and Risser (1985) showed examples of both dangerous and protective
625 driving styles. Whereas the focus of much driving style research tends to be on the dangerous
626 driving styles, it is important to discuss which driving styles contribute most to preventing crash
627 involvement. “Defensive driving” is an example of a driving style supposed to have such an
628 effect. A meta-analysis by Elvik et al. (2009) showed that defensive driving courses reduce crash
629 risk by about 20 percent for professional drivers, which is clear evidence of a relationship
630 between driving style and crash risk.

631 In summary, the studies reviewed in this section show clearly that several indicators of driving
632 style can predict crash involvement. The clearest finding is that drivers whose driving style is
633 characterised by frequent speeding and/or abrupt acceleration and deceleration have a higher
634 crash involvement. That speeding is related to crash involvement is not surprising when
635 considering the long established relationship between speed and crash probability as well as
636 severity. In the same vein, the driving styles characterised by low speed or slow

637 acceleration/deceleration are associated with lower risk. There is a continuum ranging from
638 protective driving styles like ‘defensive’ or ‘calm’ on the low-risk end to dangerous driving styles
639 like ‘aggressive’ or ‘hostile’ at the high-risk end. Speed is probably only one of the indicators
640 explaining this variation. Beyond this general formulation of a continuum from low-risk to high-
641 risk driving style, the available literature does not permit any ranking of the strength of
642 relationships between the various driving styles and crash risk. There is a need for more research
643 in order to map out these relationships in more detail in order to make quantitative estimates of
644 the predictive power of different driving styles regarding driver crash involvement, and to arrive
645 at a clearer understanding of the behavioural mechanisms involved. Thus, it could be possible to
646 place each driving style on a continuum from low to high risk. To achieve this, there is clearly a
647 need for more studies using actual crash involvement rather than self-reports for investigating the
648 predictive power of driving styles. Naturalistic driving analysis could be expected to play key role
649 here, in particular if the data includes a sufficient number of actual crashes that could be related
650 to driving style indicators. A recent, simple and innovative approach is using smartphone
651 technology for the acquisition of large amount of behavioural data in naturalistic settings. This
652 approach is now being used increasingly in research on driving styles (Johnson and Trivedi, 2011;
653 Eren et al., 2012; Paefgen et al., 2012; Hong et al., 2014).

654

655 **Factors associated with driving styles**

656 **Individual factors**

657 *Gender.* Corbett (2007) reviews research on gender differences in car-related crimes and
658 convictions as well as self-reported offenses. After pointing out the well-known overall gender
659 gap in driving styles, resulting in a higher rate of offenses and convictions among males, she
660 concludes that female driving styles are more heterogeneous, and that there is a “ladette”
661 subgroup of young female drivers, whose driving style is more similar to that of young males.

662 A comparison of young male and female drivers' attitudes and self-reported traffic behaviour
663 in Finland between 1978 and 2001 (Laapotti et al., 2003) showed that the gender difference in
664 traffic offenses (fewer offenses and lower crash rate among females) had not decreased over the
665 years. For some indicators (for example attitudes towards traffic rules and safe driving) the
666 difference had even increased somewhat. On the other hand, Boyce and Geller (2002) found no
667 significant gender differences regarding risky driving style.

668 Reagan et al. (2013) studied driving style at a more strategic level, namely seatbelt use, using
669 data from the 100-car naturalistic driving study. Based on more than 86000 trips, 134 drivers
670 (primary and secondary) were grouped into infrequent (using seatbelts on 30% or less of all trips),
671 occasional (40 – 85 %), and consistent (more than 95 %) seatbelt users. They found that 13.1 %
672 of female drivers (8 out of 61 drivers) were infrequent users, compared to 20.5 % of male drivers
673 (15 out of 73 drivers). Although this gender difference was not statistically significant, it is
674 suggestive of less frequent seatbelt use among male drivers, which is consistent with other studies
675 showing a more risky driving style among males. The authors point to the small and possibly
676 biased sample as a limitation of this study.

677 Kleisen (2011) used the MDSI to compare driving styles between male and female young
678 drivers, finding that females scored higher on the positive driving styles ('patient' and 'careful'),
679 whereas males were characterised more by negative driving styles ('risky', 'angry', 'high-velocity').

680 Gender differences in driving style seem to vary with driving conditions. For example,
681 Ericsson (2000) found that the tendency of men to accelerate harder than females was clearly
682 more pronounced on a local feeder road in a residential area compared to other road types.
683 Interactions between gender and road type was observed also in a site-based study by Aronsson
684 (2006). She found very small differences between male and female drivers in average speed over a
685 section consisting of a combination of road types. However, males tended to drive slightly faster
686 than females on suburban streets, whereas females drove faster on arterials and urban streets. In
687 addition, females tended to keep larger headways than males on suburban roads.

688 Although these results on the relation between gender and driving style are somewhat mixed,
689 existing studies indicate a general tendency for men tend to adopt a riskier driving style than
690 women. This may possibly be partly explained by innate biological factors such as testosterone
691 level (Evans, 2006) but it seems likely that also socio-cultural factors (e.g., living up to the
692 culturally defined male “ideal”; see the study by Skippon et al., 2012, cited below) play a role.

693 *Age and experience.* Keskinen et al. (1998) observed speed, acceleration, time gaps and driver
694 head movements of both turning drivers and drivers driving through an intersection, while
695 observers judged the age of the drivers. They found lower acceleration and longer turning times
696 in intersections among older compared to younger drivers, resulting in shorter time gaps for the
697 older drivers. Similarly, Yan et al. (2007) studied driving behaviour related to left-turn gap
698 acceptance in a simulator, and found that older drivers (56 to 83 years old), especially female
699 drivers, had more problems with left-turn manoeuvres, compared to younger drivers. At the
700 same time, they displayed a conservative driving attitude as a compensation for reduced driving
701 ability.

702 De Waard et al. (2009) found, in a simulator study, that older drivers (65 years and over) kept
703 a lower speed than younger drivers when merging into heavy motorway traffic. They point out
704 that this may make the merging manoeuvre more risky in real traffic. In this study they
705 manipulated length of the acceleration lane as well as presence of a driver support system that
706 encouraged drivers to speed up if the speed was too low, both of which facilitated merging.

707 Reimer et al. (2013) compared three age groups regarding lane choice and changing in real
708 traffic using an instrumented vehicle. They found that drivers in their 60’s were less likely to
709 change lanes and to drive on the leftmost lane compared to younger drivers. They also found that
710 increased cognitive workload decreased frequency of lane change in all age groups.

711 Underwood (2013) studied changes in driving styles among two age groups of novice drivers
712 (17-19 years and 23-44 years) over the first 6 months after they acquired a full license, in order to
713 assess effects of driving experience. The drivers were tested in an instrumented vehicle in real

714 traffic on three different occasions, zero, three, and six months after passing the driving test. The
715 drivers tended to increase their speed over the three drives, as well as their frequency of cutting
716 across the central lane marker on bends. The older group of novice drivers showed stronger
717 indications of becoming more cautious with driving experience, as shown by increased headway
718 and more glances in the mirrors at critical points, compared to the younger group. The author
719 comments that the observed changes across the three drives are partly an effect of general driving
720 experience over the six-month duration of the test period, but that there may also be an effect of
721 familiarity with the instrumented vehicle and the testing procedure. Thus, to the extent that the
722 effects are due to general driving experience, there seems to be an interaction between age and
723 driving experience regarding driving style.

724 Age effects on driving styles were also observed by Boyce and Geller (2002). They measured
725 several variables (e.g., vehicle speed, following distance and seatbelt use) during an on-road test
726 with an instrumented vehicle and found that young age (between 18 and 25 years old) is one of
727 the predictors of risky behaviours (speeding and following distance).

728 The previously mentioned study by Reagan et al. (2013) of seatbelt use, using data from the
729 100-car naturalistic driving study, also looked at age differences and found that younger females
730 (under 40 years) were more likely to be infrequent seatbelt users than females over 40. For males
731 there was no significant age effect.

732 Older studies of age differences in driving styles were summarised by Elander et al. (1993, p.
733 287), who conclude that faster speed is associated with younger drivers and that in addition
734 “several observational studies have found relationships between youth and other potentially risky
735 driving styles”. The latter include shorter headways to vehicle in front, accepting shorter time
736 gaps when pulling out into traffic, and running yellow lights.

737 This clearly indicates that young drivers generally adopt more aggressive/risky driving styles
738 and older drivers tend to be more cautious than average. The latter may, however, lead to risky
739 situations due to the problems of some older drivers to keep up with the traffic pace. This

740 indicates that the balance between excitatory and inhibitory motives change with age, with a
741 stronger excitatory dominance for young drivers. Stronger excitatory motives for young drivers
742 may be due to a range of factors including biological dispositions, group pressure from peers for
743 young drivers to “show off”, not wear seatbelt etc. Weaker inhibitory motives in young drivers
744 may be due to weaker risk perception due to less driving experience or a lower level of cognitive
745 maturity among younger drivers (at least for mid-teenage drivers). Based on a literature review,
746 Casey et al. (2011) suggest that the high prevalence of impulsive and risky choices among
747 adolescents can be explained as “an imbalance between a heightened sensitivity to motivational
748 cues and immature cognitive control”. Similarly, the more defensive driving styles typically
749 adopted by older drivers could possibly also be explained in terms of weaker excitatory motives
750 for risky behaviour (e.g., biological factors related to ageing such as lower testosterone level and
751 socio-cultural norms for how older people are expected to behave) as well as relatively stronger
752 inhibitory motives (e.g., a need to compensate for biomechanical or perceptual impairments.)

753 *Personality and lifestyle-related factors.* Some studies have looked at associations between driving
754 styles and personality factors. For example, Poo and Ledesma (2013) found that several
755 personality traits correlated significantly with MDSI driving style factors. Positive correlations
756 were found between self-reported impulsive sensation seeking and risky, angry and dissociative
757 driving styles, between aggression-hostility and risky and angry driving styles, and between
758 neuroticism-anxiety and dissociative driving style. Self-reported impulsive sensation seeking and
759 aggression-hostility correlated negatively with careful driving style.

760 Skippon et al. (2012) present two studies of personality and driving styles and discuss their
761 results in the perspective of driving styles as indicators of reproductive fitness (p. 370):

762driving in a particular style does indeed convey information about the five-factor
763 personality profile of the driver to other people. It also confers information about the likely
764 age, gender and relationship status of the driver. So, for instance, if a young male is motivated
765 to signal his youth, maleness and spontaneous, dominant personality to females, the faster,

766 riskier, more aggressive driving styles represent good ways to do so; females will read and
767 understand the signals. Likewise an older female might make use of Patient or Cautious
768 driving styles to signal maturity, agreeableness and propensity for long-term relationships.
769 (Skippon et al., 2012, p. 370).

770 One of the studies consisted of having participants read descriptions of the eight driving styles
771 of the Multidimensional Driving Style Inventory MDSI, and then judging how well each of a list
772 of 18 personality and behaviour characteristics would fit a driver who would normally show the
773 behaviours described by the driving styles. The characteristics to be judged consisted of
774 personality traits based on the five-factor theory, as well as attributions of status, gender, age,
775 relationships and attractiveness. The five-factor theory - «Big Five» - is a widely accepted model
776 of human personality, comprising the dimensions “openness”, “conscientiousness”,
777 “extraversion”, “agreeableness”, and “neuroticism”. Some of the findings were that the
778 “cautious” driving style was associated with high scores on conscientiousness and agreeableness,
779 whereas the “angry” driving style scored low on the same dimensions. The findings were
780 interpreted as tentative support for the ideas quoted above.

781 Further support for a relationship between negative driving styles and personality factors
782 comes from studies by Lajunen and Summala (1995) and Boyce and Geller (2002). Lajunen and
783 Summala (1995) found that high scores on the ‘driving aggression’ factor of the Driving
784 Behaviour Inventory DBI were related to neuroticism ($r=0.56$), Type A personality (described by
785 Friedman [1996] as characterised among other things by over-ambitious and impatient behaviour)
786 ($r=.32$), low self-esteem ($r=-0.34$), and a low sense of coherence ($r=0.52$). Boyce and Geller
787 (2002) found that younger age (between 18 and 25 years old) and Type A personality are
788 predictors of risky behaviours. Type A correlated significantly with mean speed ($r=0.33$) and
789 mean following distance ($r=-0.30$).

790 Concerning life style, two Danish studies (Møller and Sigurdardottir, 2009; Møller and
791 Haustein, 2013), studying associations between driving style, as measured by a 14-item

792 customised questionnaire, and leisure activities. They found that the driving style factors Thrill
793 and Anger were most strongly related to the lifestyle factors “cruise around in a car with friends”
794 and “driving to friends”.

795 As shown by several studies, personality characteristics are clearly associated with driving style.
796 More specifically, the results seem to indicate that drivers with certain personality types (e.g.,
797 Type A) are particularly disposed towards risky driving behaviours. In terms of the present
798 framework, this can be understood as an association between those personality types and
799 stronger excitatory motives for risky behaviours. However, the actual biological and psychological
800 mechanisms underlying this relation are still unclear.

801 *Cognitive style.* Kleisen (2011) found that driving styles of young drivers, as defined by the
802 Multidimensional Driving Style Inventory MDSI, were significantly related to scores on a
803 questionnaire about *thinking styles*. Thinking style is related to the more common concept of
804 *cognitive style*, although Kleisen consider those as different categories. Out of thirteen thinking
805 styles, three (“executive”, “hierarchic”, and “conservative” thinking style) correlated positively
806 and significantly ($p < 0.001$) with the “patient” and “careful” driving styles. Hierarchic thinking,
807 which is characterised by multi-tasking, and multiple goals with different priorities, showed a
808 stronger association with the positive MDSI driving styles in female drivers than in males. This
809 result suggests the notion that drivers with stronger executive control abilities are better equipped
810 to resist momentary impulses for potentially unsafe behaviours (e.g., unsafe overtaking, speeding,
811 hostile aggression or taking the eyes off the road to send a text message).

812

813 **Socio-cultural aspects**

814 *Social network and organisational culture.* Based on our framework, it is expected that the shared
815 values within groups such as families and friends or organisations (e.g., the attitude towards
816 unsafe driving among friends or the safety policies adopted in a truck fleet), affect drivers’
817 motives and hence influence driving style. This notion is supported by existing data. Taubman-

818 Ben-Ari and her colleagues found significant associations between parents' and offsprings'
819 driving style (Taubman-Ben-Ari et al., 2005). In another study of 413 pairs of intimate partners
820 (Taubman-Ben-Ari, 2006), they found significant associations between driving styles of couples.
821 In discussing results from these studies, they focused on the importance of intra-familial
822 transmission of driving styles as a basis for planning and designing effective safety interventions.
823 Further studies by the same authors focused on the relationship between family climate and the
824 driving styles of young drivers (Taubman-Ben-Ari, 2010; Taubman-Ben-Ari and Katz-Ben-Ami,
825 2012; 2013), finding that "positive aspects of the parent-child relationship and high levels of
826 conformity to authority were related to greater endorsement of the careful driving style".
827 Correlations in driving styles between parents and children have been found also by Bianchi and
828 Summala (2004).

829 Social influence seems to be important for driving styles especially among young people. For
830 example, Møller and Haustein (2014) found that young drivers' perception of speeding among
831 their friends was by far the most important predictor of own speeding behaviour, compared to
832 other possible predictors like education, age, car use, history of crashes and violations, attitudes
833 to speed limits, and perceived crash risk.

834 It has been shown in several studies that there is a relationship between safety culture or safety
835 "climate" of an organisation, and the risk of accident involvement among its employees (see e.g.
836 Nahrgang et al., 2011, for a meta-analysis of relevant studies). It seems reasonable to assume that
837 this relationship is mediated to a large extent by effects of safety climate (i.e., values related to
838 road safety) on driving styles. Recent support for this assumption comes from a study by Zohar
839 et al. (2014), who showed that a low frequency of hard-braking events among long-haul truck
840 drivers was related to a positive assessment of the safety climate of their organisation.

841 *National and regional differences.* The road safety values associated with a country or region would
842 also be expected to significantly influence on driving styles adopted. An interesting approach to
843 national and regional differences in driving style is the "social accident" model proposed by

844 Factor et al. (2007). They discuss interaction between different social groups in traffic from a
845 sociological perspective, stating that drivers belonging to different social groups interpret a given
846 situation differently, and that this may result in conflicting decisions, possibly leading to crashes.
847 The article by Factor et al. (2007) refers to several previous studies showing systematic
848 differences in traffic behaviour between drivers of different nationalities. For example, Gregory
849 (1985) studied driving characteristics in Egypt, and Edensor (2004) compared driving habits
850 between Britain and India. Both India and Egypt have a lower level of road traffic legislation and
851 enforcement than Western countries, and this seems to result in culturally determined informal
852 rules, for example:

853 In Alexandria, when a driver wishes to proceed ... by pulling out into traffic ... from a side
854 street, he will appear not to wait for an open space in the mass of movement, but will simply
855 plunge ahead. The abstract conception that a space will eventually open up for him is not
856 considered (Gregory, 1985, p. 344).

857 Concerning India, the road traffic system is characterised by informal conventions and norms
858 for driving, possibly due to a paucity of formal rules:

859 For instance, many vehicles lack rear-view mirrors and so the monitoring of traffic behind is
860 usually not carried out. This means that it is necessary to sound the horn to warn any vehicle
861 of a desire to overtake, and this has become accepted custom, irrespective of the presence or
862 not of mirrors (Edensor, 2004, p. 114).

863 Indirect evidence of national differences comes from a recent comparison of traffic safety
864 culture between China, Japan and the United States (Atchley et al., 2014). Although they do not
865 explicitly discuss driving styles, they conclude that the different crash risk records of the three
866 countries are related to different cultural values. Whereas China is characterised by an emerging
867 driver population and cultural values resulting in aberrant driving behaviours and many crashes,
868 Japan has a more established driver culture with a stronger emphasis on risk reduction. In the

869 United States, the focus on individual freedom leads to choices that result in higher crash risk
870 than in some other Western countries.

871 Two additional articles addressed road safety and driving styles in Pakistan and Slovenia,
872 respectively. Batool et al. (2012) did a qualitative study of road safety in Pakistan, consisting of
873 semi-structured interviews with government officials, researchers, and road users in order to map
874 characteristic deviant driving styles in the country, as well as needs for road safety measures in
875 general. Regarding the cultural aspect of driving styles, the following conclusion seems pertinent
876 (p.45): "... there is no inclination among the population in Pakistan toward safe driving habits.
877 The main point of contention here is the kind of safety culture that allows bad driving habits to
878 develop. In the opinion of study participants, if you have to drive in the country, you have to
879 blow your horn, and you must overtake fellow drivers or neglect their right of way. Even if
880 people try to follow the rules, society forces them to be involved in unsafe practices."

881 Persak (2011) discussed human factors aspects of road crashes and dangerous driving in
882 Slovenia, concluding among other things that driving aggressiveness and other psychological
883 characteristics of drivers are major problems, and that the "Slovene national personality profile"
884 provides favourable conditions for deviant traffic behaviour, like fast driving styles. Social
885 desirability seems to be one explanation of fast driving, since this behaviour is viewed positively
886 by the Slovene society.

887 Thus, there seems to be convincing evidence for the influence of national or regional culture
888 on the driving styles adopted in the region. We refer to the article by Factor et al. (2007) for
889 additional references to studies of differences between countries.

890

891 **Technological factors**

892 In presenting our conceptual framework we pointed to the possibility that driving styles may
893 be influenced by technological factors. There are several studies showing that drivers adapt their

894 behaviour to various characteristics of the vehicle or the traffic environment. For example, when
895 anti-lock braking systems (ABS) were first introduced, it was shown that some drivers changed
896 their driving behaviour. Among the observed behavioural changes was a tendency to keep shorter
897 headways (Sagberg et al., 1997).

898 However, for such behavioural adaptations to count as driving styles according to our
899 definition, it has to be shown that this is a relatively permanent change in behaviour and that it
900 differs between (groups of) drivers. Future research is needed to determine the degree to which
901 individual drivers adapt differently to e.g. in-vehicle driver information and support systems. If
902 such differences are found, it is an interesting question to what extent the technological factors
903 interact with the other driver background factors discussed above, in explaining driving styles.
904 Such knowledge will be important for possible applications of technological systems for
905 modifying driving styles, a topic that will be discussed below.

906 In summary, the studies reviewed in this section clearly indicate that driving style is potentially
907 influenced by a range of factors, from individual characteristics (gender, age, cognitive style, and
908 lifestyle) to group/organisational values and national/regional culture. Thus, it seems clear that
909 driving styles often develop through the joint influence of a large number of individual, socio-
910 cultural, and technological factors. However, further research is clearly needed to better
911 understand the precise mechanisms for how these different factors influence driving style and
912 how they may interact.

913

914 **Applications of driving style research**

915 Understanding driving styles is of great interest to many businesses (e.g., automotive industries
916 and insurance companies) as well as to the drivers themselves. This is because driving style affects
917 fuel consumption, vehicle maintenance bills, insurance cost, safety, etc. Today a rapidly growing
918 number of companies offer driver behaviour profiling, coaching and safety management services

919 targeting commercial vehicle fleet operators as well as the insurance industry. The trend to link
920 insurance premiums to driving style can be viewed in the larger context of Usage-Based Insurance
921 (UBI) or pay-as-you-drive (PAYD) schemes (see e.g. Ellison et al., 2015a; 2015b).

922 A key application of knowledge from driving style research is in the development of methods
923 for modifying driving style. Despite driving styles being, by definition, “relatively stable”
924 characteristics of the driver (Saad, 2004), some approaches can be used to change driving styles,
925 aiming to eradicate maladaptive (negative) driving styles and reinforce adaptive (positive) ones.
926 Those approaches include driver training and education, increasing awareness of dangerous
927 situations, and Behaviour Based Safety (BBS) techniques.

928 Driver training and education is a common technique to change driving style. Gregersen
929 (1994) compared two groups of learner drivers, one group receiving training only by a lay person
930 (most often a parent), and the other group receiving a combination of training by a lay person
931 with traffic school instruction. The self-reports of driving style, collected after the training,
932 showed a small difference in the direction of more careful driving style in the group receiving
933 professionally supported training. Further evidence of training effects on driving styles comes
934 from a meta-analysis of courses in defensive driving (Elvik et al., 2009), finding a decrease in
935 crash risk by about 20 percent among professional drivers.

936 Letting drivers see and study their own history of driving data is another method that could be
937 used to modify driving behaviour towards safer driving styles, as shown by Takeda et al. (2011).
938 Their results suggest that the drivers’ ability to understand dangerous situations can be improved
939 by using driving data, as indicated by a 50% reduction in the number of dangerous events for a
940 group of “non-expert” drivers, compared to a much smaller reduction in a group of “expert”
941 drivers.

942 Another approach to modification of driving styles is using Behaviour Based Safety (BBS)
943 techniques. Although this is an approach for reinforcing safe behaviour in general, it is applicable
944 to driving style modification to the extent that it produces lasting changes in driving behaviour (af

945 Wählberg, 2007). The key idea behind BBS programmes is to target at-risk behaviour and
946 provide later feedback to employees in several working contexts, including the automotive
947 domain (Hickman et al., 2007; Hickman and Hanowski, 2010). In BBS programmes for drivers,
948 video-based On Board Monitoring Systems (OBMS) is a potentially useful tool for identifying
949 safety-critical behaviours (Horrey et al., 2012; Socolich & Hickman, 2014). Lytx DriveCam and
950 SmartDrive Safety are examples of drivers' feedback and coaching services provided through
951 OBMS. Two studies of the DriveCam programme, one with teen drivers (McGehee et al., 2007)
952 and one with long-haul and short-haul carrier drivers (Hickman & Hanowski, 2011) have
953 reported that behaviour feedback/coaching programme produced a significant decrease in
954 participants' number of safety-relevant events, showing that in-vehicle feedback and back-office
955 feedback/coaching can modify driving behaviour towards safer driving styles.

956 The present framework offers some concrete guidance with respect to driving style
957 modification. A first key implication is that lasting modification of driving style necessarily
958 involves changing drivers' values and motives. For example, a stand-alone on-board system
959 alerting the driver when exceeding the legal speed limit will not be expected to have any major
960 lasting effects on driving style unless tied to incentives that motivate the driver to change his/her
961 behaviour. The same issue probably applies to training programs that are mainly instructional;
962 that is telling the driver what to do differently but not addressing the driver's motivation for
963 learning and adopting a safer driving style.

964 Another, somewhat different, application of driving style research is the identification of who
965 is behind the wheel (Wakita et al., 2005; Miyjama et al., 2007; Wahab et al., 2009; Aljaafreh et al.,
966 2012). Such models take advantage of the fact that habitual, automatised, vehicle control
967 behaviour (e.g., steering patterns), are often characteristic for each driver. This in turn could be a
968 basis for many applications such as providing personalised settings to the drivers, for both
969 advanced driver assistance systems and in-vehicle information systems, (Sakaguchi, 2003;
970 Ungoren and Peng, 2005; Cho et al. 2006; Xiong et al., 2012).

971

972 **Discussion and conclusions**

973 As is clear from the present review, existing driving style research has generally been
974 conducted without a common underlying framework for conceptualising key terms and
975 theoretical constructs. This is evidenced by the variety of existing definitions of driving styles as
976 well as the rather arbitrary “common sense” labelling of driving style categories commonly used.
977 This makes the results from different studies difficult to compare, synthesise and generalise.

978 The present paper represents an initial attempt to synthesise findings from existing driving
979 style research based on a novel tentative theoretical framework for understanding the concept of
980 driving style. We define driving style broadly as “a habitual way of driving, which is characteristic
981 for a driver or a group of drivers” and suggest that the development of driving styles may be
982 viewed in terms of a process of habit formation driven partly by driver motives determined both
983 by individual factors, by socio-cultural values and norms, and by technology. We further
984 proposed a distinction between global and specific driving styles. Global driving styles may be
985 viewed in terms of *sets* of habitual behaviours reflecting similar underlying motives (e.g., the basic
986 motive of expediency may be reflected in speeding, close following and a large proportion of
987 time spent in the left lane). By contrast, specific driving styles refer to individual habitual
988 behaviours (e.g., speeding, close following).

989 Existing literature addressing global and specific driving styles was reviewed, showing that
990 there is a relatively large body of research on the topic, including both observations of actual
991 driving behaviour and self-reported data. The review also addressed the relation between self-
992 report instruments and observed behaviour and concluded that the two types of methods
993 generally yield significantly correlated results. For speeding behaviour correlations above 0.60
994 have been reported, but for other driving styles the magnitudes of the correlations are often

995 relatively weak. This indicates a value of self-report instruments but also that caution is needed
996 when generalising from self-reported data to actual on-road behaviour.

997 Moreover, several studies have found a significant association between driving styles and
998 different proxies for crash risk, in particular self-reported crash involvement. The clearest finding
999 is that crash involvement is predicted by speeding and by a high frequency of driving-related
1000 violations, which are typical characteristics of aggressive or impatient driving styles. It was
1001 suggested that the analysis of naturalistic driving data, where real crashes may be related to
1002 continuous “normal driving” data, may be a fruitful avenue for future research on the relation
1003 between driving styles and crash risk.

1004 We also reviewed the literature on factors influencing driving styles and found evidence that
1005 driving styles are potentially determined by a variety of individual and socio-cultural factors
1006 including gender, age, driving experience, personality, cognitive style, group and organisation
1007 values as well as the general national/regional culture. However, further research is clearly needed
1008 to better understand more precisely *how* these factors shape driving style and how they may
1009 interact. The initial framework sketched out here may serve as a starting point for framing more
1010 precise hypotheses guiding future empirical investigation on how driving styles are established.
1011 The review also found evidence that driving styles can be modified by various behaviour-based
1012 techniques, and that such modification also can contribute to reductions in crash involvement.
1013 For example, evaluation studies of courses in defensive driving (Elvik et al., 2009) have shown
1014 significant decreases in crash risk. Again, the proposed framework offers some concrete
1015 suggestions for when driving style modification would be expected to be most efficient. In
1016 particular, it emphasises that training and behavioural feedback needs to be supported by changes
1017 in drivers’ motives to have any lasting effects.

1018 The relative importance of the various factors influencing driving style needs further
1019 investigation. For example, how strong are the effects of the “Big five” personality factors
1020 compared to effects of cultural conventions of a certain region or country? Is the potential for

1021 modifying driving styles related to background factors? Conceivably, driving styles that are
1022 strongly anchored in the driver's personality may be more difficult to modify than habits formed
1023 more by socio-cultural norms. Enhanced knowledge of such relationships could have
1024 implications for recruitment and training of professional drivers, and for effective use of driving
1025 assistance systems.

1026 Applications of the knowledge of driving styles are wide. Beyond driver training, driver
1027 coaching, and usage-based insurance, driving style research could also lead to the development of
1028 non-intrusive means for driver identification and to approaches for adjusting driver assistance
1029 systems to individual driving styles.

1030 In summary, the reviewed research demonstrates the multidimensionality and complexity of
1031 the concept of driving styles. A thorough understanding of driving styles and their implications
1032 for traffic safety measures necessitates consideration of behavioural indicators and measures, as
1033 well as individual background factors (like attitudes, motives, self-assessment, cognitive styles,
1034 driving experience, etc.), socio-cultural factors (group/organisational values and societal norms)
1035 as well as technology (e.g., driving assistance functions). Our current understanding of the
1036 relationships between all these different aspects of driving styles is limited by the lack of a
1037 common theoretical model. The tentative framework suggested here could be a first step towards
1038 generating testable predictions on how driving styles are established and modified, which could
1039 then be tested in future empirical studies.

1040

1041 **Key Points**

- 1042 • Driving styles and the relationships between the different aspects of driving styles are still
1043 poorly understood, largely due to the lack of a common conceptual framework.
- 1044 • This paper outlines an initial framework which was used to structure the review and
1045 potentially offers a theoretical foundation for future driving style research.

- 1046 • Naturalistic driving observations represent promising approaches to future research on
1047 driving styles.
- 1048 • Despite the fact that driving styles are poorly understood, there is clear evidence that
1049 some indicators, e.g. related to speed and acceleration, as well as a high prevalence of
1050 violations, are predictive of crash involvement risk.
- 1051 • Applications of the knowledge of driving styles are wide, including behaviour
1052 modification, usage-based insurance systems, and driver profiling for driver assistance
1053 systems.

1054

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