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FATIGUE IN THE ROAD TRANSPORT SECTOR

By

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ACRONYMS

Acronym	**Term**
DOT	Department of Transportation (U.S.)
ETSC	European Truck Safety Council
FMCSA	Federal Motor Carrier Safety Administration (of the U.S. DOT)
FRMS	Fatigue Risk Management System
HGV	Heavy Goods Vehicle (= large truck)
HoW	Hours-of-Work
LDW	Lane Departure Warning
LTCCS	Large Truck Crash Causation Study (U.S.)
NAFMP	North American Fatigue Management Program
NTSB	National Transportation Safety Board (U.S.)
OSA	Obstructive Sleep Apnea
PERCLOS	Percent eye closure (alertness measure)

1. INTRODUCTION

No topic relating to commercial truck and bus driver safety and regulations has received more study and notoriety over recent decades than has driver fatigue and alertness. Commercial drivers, especially long-haul drivers, face numerous challenges to getting sufficient sleep and rest. These may include:

- Limited sleep during principal sleep periods.
- Extended work hours (plus long commutes for many drivers)
- Changing, rotating, or split-sleep work schedules
- Unpredictable schedules with short-notice changes
- Schedules conflicting with natural circadian rhythms
- Unfamiliar and/or uncomfortable sleep environments
- Difficulty finding safe and quiet rest parking
- Stress from tight delivery schedules and uncontrollable delays
- Pay by the mile or kilometre, which may incentivize overwork
- Inadequate physical exercise
- Poor diets
- Environmental stressors (e.g., heat, cold, lack of ventilation).

Over-the-road bus (motorcoach) drivers can face additional challenges, including lack of sleeper berths, lack of privacy for rest, and frequently needing to drive while others are sleeping. Asleep-at-the-wheel bus crashes can cause catastrophic harm.

Focus on commercial driver fatigue is heightened by the economic impacts of Hours-of-Work (HoW) rules. Impacts are felt at the personal, company, and national levels, and with a strong perceived conflict between the interests of safety and prosperity. Industry and drivers generally seek more lenient rules, while many in the public favor more restrictions.

Driver fatigue has been characterized as the biggest safety problem in truck transport, and inextricable from drivers' long working hours. The bulk of evidence, however, suggests that fatigue is not among the *top* safety problems and, further, that fatigue is not primarily due to excessive work *per se*. Rather, a person's alertness primarily reflects his or her physiology, lifestyle, and overall health. Commercial drivers do face formidable job-related health and lifestyle challenges, however. And while fatigue may not be the biggest cause of Heavy Goods Vehicle (HGV) crashes, it is an important cause, especially in crashes where HGV drivers themselves are killed or injured. Further, driver fatigue and stress may cause long-term impaired health and several specific life-threatening illnesses.

1.1 What is Fatigue?

Driver fatigue defies easy definition. It is a hypothetical construct, something that we know exists, but which is not *directly* observable. Unlike alcohol or drug-related impairment, fatigue has no known unitary underlying mechanism or marker. It is manifested in multiple ways, including physiology, cognition and performance, subjective experience (i.e., drowsiness), and general health and wellness. Driver fatigue is clearly not the same as physical fatigue from exertion. In fact, physical exertion is more likely to increase alertness than to decrease it (O'Neill et al., 1999).

A loose working definition of fatigue in driving is "drowsiness, and whatever else might be associated." Drowsiness (sleepiness) is certainly the dominant feature in driving. Various specific indicators are discussed below, and also shown in the textbox (Knipling, 2009a; NAFMP, 2013).

1.2 Measures & Indicators of Fatigue

Driver fatigue may be detected and measured both by performance measures and by physiological measures. On some measures, the two are highly synchronized. Driver performance is best measured by lane tracking; e.g., the standard deviation of lateral lane position. Other performance measures include steering patterns, speed maintenance, and vehicle following. Driver performance may also be measured in responses to driving events; examples include decision choices and reaction times for avoidance maneuvers in response to crash threats. Fatigue can result in mental "state instability" manifested in a variety of cognitive and performance errors (Phillips, 2014) though such conditions defy easy definition and measurement.

Signs of fatigue while driving:

- **Drowsiness**
- **Tunnel vision; reduced effective field of view**
- **Microsleeps (brief losses of consciousness)**
- **Eyes:**
  - **Eyelid droop**
  - **Periodic loss-of-focus**
- **Yawning**
- **Thoughts:**
  - **Wandering, disjointed**
  - **Scattered, dreamlike visions**
- **Head movements:**
  - **Gentle swaying**
  - **Spasmodic jerks**
- **Body movements:**
  - **Fidgeting, shifting positions**
  - **Adjusting windows, radio, ventilation**
- **Vehicle control:**
  - **Weaving (progressive)**
  - **"Drift & jerk" steering**
  - **Variable speed**
- **Delayed or incorrect responses to traffic events.**

Source: Knipling (2009a)

PERCLOS (percent eye closure) is proportion of time that drivers' eyes are 80-100% closed. It is a measure of slow eyelid closure not inclusive of eye blinks. PERCLOS is well-validated as a continuous measure of alertness. Correlations of +0.8 to +0.9 with lane tracking deterioration (Wierwille, 1999) and with attentional lapses (Dinges et al., 1998) have been reported. Research and development over several decades has sought a video sensor/processor to unobtrusively measure PERCLOS in vehicles and provide appropriate warnings to drivers about their alertness levels. No robust commercial system is available, though such products will likely emerge in the near future.

Other physiological alertness measures include brain electroencephalogram (EEG), electrooculogram (EOG), heart rate variability (Vagal Tone), measures of body activity (e.g., from wrist-worn activity watches), and sleep latency (time to fall asleep when given opportunity). Applications to real driving are limited, however, because the measures are obtrusive and/or highly variable both within and between subjects.
Subjective self-rating scales include the Stanford Sleepiness Scale (SSS) and the Karolinska Sleepiness Scale (KSS). However, subjective self-ratings do not correlate well with objective measures of alertness (Wylie et al., 1996; Van Dongen and Belenky, 2012). Drivers may know they are sleepy, but they don't know how sleepy, or how imminent loss of consciousness might be (Itoi et al., 1993). In the U.S., interviews with 312 motorists who had fallen asleep and crashed found that almost half had no expectation at the time that they might lose consciousness (Stutts et al., 1999). Thus the need for objective measures.

Several large, U.S. Department of Transportation (DOT) sponsored HoW-related studies have implicitly treated crashes (e.g., Jovanis et al., 2011) and Naturalistic Driving "Safety-Critical Events" (e.g., Hanowski et al., 2008; Blanco et al., 2011) as indicators of driver fatigue. This is unwarranted scientifically since only a relatively small minority of such events are verifiably fatigue-related (Knipling, 2015b). As with any psychological construct, operational measures of fatigue must have construct validity; that is, converging evidence that they actually measure the conceived concept.

2. FATIGUE IN TRUCK & BUS CRASHES

2.1 Risk-Cause Model

Efforts to reduce fatigue-related crashes require an understanding of how fatigue operates to cause crashes. Figure 1 shows a simplistic "Risk-Cause" model (Knipling, 2009a). Shown is a conceptual crash timeline with two types of causal factors: predisposing risk factors and proximal causes. Risk factors set up a probability that driver errors or other proximal failures occur or have greater consequences. Proximal causes are the discrete triggering driver mistakes, driver misbehaviors, vehicle defects, or other triggering failures.

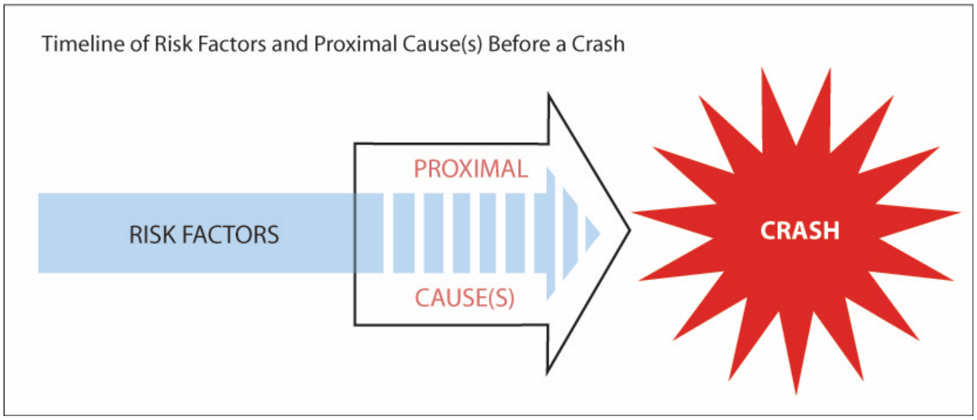

Figure 1. Timeline of risk factors and proximal cause(s) before a crash. **Knipling (2009a).**

2.2 Principal Crash Causes & Risk Factors

There are many categories and types of risk factors affecting the probabilities of a crash. Major categories include:

- Enduring driver factors; e.g., gender, personality, medical conditions
- Temporary driver factors; e.g., mood, recent sleep, time-of-day, drug use, road familiarity
- Vehicle; e.g., mechanical condition, safety features & technologies
- Roadway and environmental; e.g., divided vs. undivided, traffic density
- Company operations & management; e.g., training, driver monitoring & evaluation
- Government policies & practices; e.g., driver licensing, HOS rules, enforcement practices.

Proximal causes also fall into multiple categories. The Large Truck Crash Causation Study (LTCCS) performed in-depth investigations of 963 large truck crashes stratified and weighted to be representative of the U.S. serious truck crash population. The LTCCS classified proximal causes (termed Critical Reasons) into six main categories, four of which were types of driver errors. A Critical Reason was designated and assigned to one involved vehicle. This could be considered an assignment of "fault," though not necessarily in a legal sense. Table 1 shows LTCCS percentages for crash causal categories (Knipling, 2009a).

Table 1 - Critical Reason (CR) Categories for LTCCS Truck Crash Involvements

Critical Reason Category	Major CR Examples:	% of Truck At-Fault Crashes	% of All Crashes
Driver Physical Failure	o Sleep-at-the-wheel o Heart attack	12%	6%
Driver Recognition Failure	o Inattention o Distraction (internal or external) o Looked but did not see	29%	16%
Driver Decision Error	o Too fast for conditions o Following too closely o Misjudgment or false assumption	38%	21%
Response Execution Error	o Overcompensation o "Sloppy" maneuver	5%	3%
Unknown Driver Error/Other	o Truck driver errors not classifiable	4%	2%
Truck Vehicle Failure	o Brake failure (full or partial) o Tire failure o Cargo shift	10%	6%
Environment: Highway Or Weather	o Road signs/signals missing o Road design o Weather and/or slick roads	2%	1%
CR Not Assigned to Truck	o Other motorist driver errors o Other motorist vehicle failure o Other non-truck-related factor	NA	45%
	Total:	100%	100%

2.3 Fatigue Crash Characteristics

Most fatigue-related crashes occur when drivers are alone, a common situation for HGV drivers. As they become sleepy, drivers gradually relinquish control of the vehicle. Steering movements, ordinarily fine and frequent, become erratic with a pattern of "drift and jerk," and then fade altogether. Consequently, most known fatigue crashes involve a drift-out-of-lane vehicle trajectory. The typical fatigue-related crash occurs on a straight, rural highway during the early morning hours between 2:00 and 7:00am. In the LTCCS, truck driver asleep-at-the-wheel was strongly related to time-of-day. Sixty-two percent (62%) of truck driver asleep-at-the-wheel crashes occurred in the two-hour period between 4:01am and 6:00am. Only 20% occurred in the 14 hours between 6:01am and 10:00pm. Fatigue crashes often involve rollovers, impacts with fixed objects, or impacts with oncoming vehicles. Thus, they are often severe.

Figure 2 shows (a) 24-hour U.S. large truck fatal fatigue crash rates (Knipling, 2009a; Massie et al., 1997) and (b) overall truck injury/towaway crash rates (Brewster & Short, 2014). Both relative rates are indexed to the 24-hour average (shown as 1.00). The curves are from two different studies, but are shown here side-by-side to demonstrate the difference between *fatigue* crash risk and *overall* crash risk for HGVs. Fatigue risk is greatest in the early morning, with a slight bump in mid-afternoon. Overall crash risk is greatest during the day when traffic density is greatest. Efforts to restrict truck night driving may be beneficial in regard to driver fatigue but are probably detrimental in regard to overall safety if truck traffic shifts to daytime. The European Truck Safety Council (ETSC, 2011) has also reported truck crash frequencies several times higher during daytime than overnight.

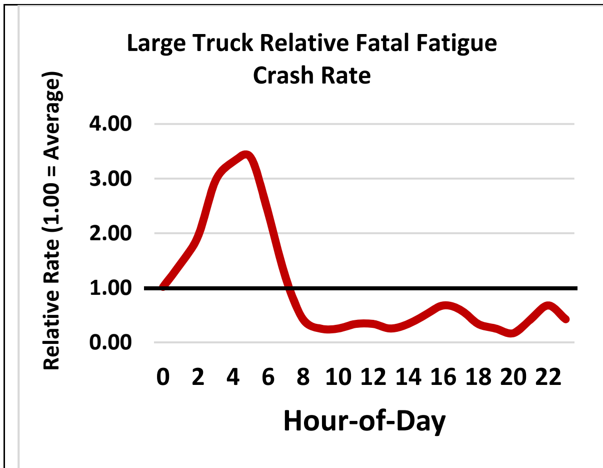

Figure 2a. 24-hour large truck relative fatal fatigue crash rate. **Knipling, 2009 from Massie et al., 1997.**

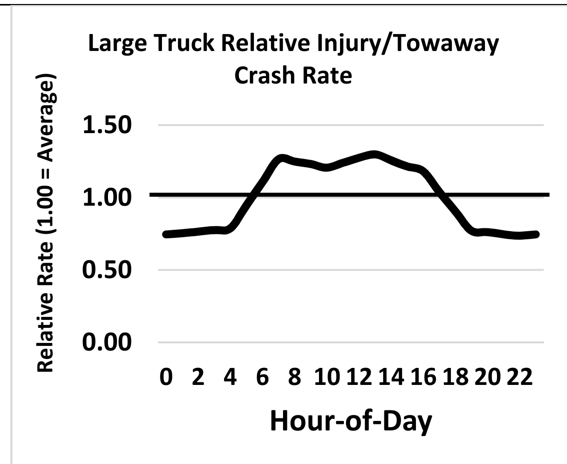

Figure 2b. 24-hour large truck relative injury/towaway crash rate. **Brewster & Short, 2014.**

2.4 Quantifying the Role of Fatigue

Quantitative estimates of the role of fatigue in truck and bus crashes vary widely due to varying criteria, target crash populations, and scientific rigour. The best U.S. information source is arguably the LTCCS. About 7% of at-fault truck crash involvements and 4% of all involvements were attributed to truck driver falling asleep at the wheel as the Critical Reason. Fatigue was judged present, though not necessarily contributory, in 13% of all truck involvements. Of course, other crashes could have had undetected fatigue. Pierre Thiffault of Transport Canada has written extensively on "hypovigilance" as an early or partial state of sleepiness which likely contributes to many crashes not identified by investigators as fatigue-related (Thiffault, 2011).

The European Truck Accident Causation (ETAC; IRU 2007) study was similar to the LTCCS and had similar findings. ETAC investigated 624 serious crashes and found fatigue to be the main cause in 6%. More than one-third of these were fatal, attesting to the high severity of many fatigue-related crashes.

Though it provides videos of driver faces to assess alertness, naturalistic driving has to date proved unsatisfactory for quantifying driver fatigue. Naturalistic driving "Safety-Critical Events" are detected from abrupt driver responses, whereas a drowsy driver's responses are fading. In a study of tractor-semitrailer SCEs, only one (1) of 915 SCEs was attributed to asleep-at-the-wheel. Few believe the problem to be this small (Knipling, 2009a, 2015a, 2015b).

Surveys of driver fatigue often indicate startlingly high incidence. For example, Häkkänen and Summala (2000) reported that 40% of Finnish long-haul drivers and 21% of short-haul drivers have problems staying alert on 20% of their drives. These and similar survey responses attest to the existence of the problem, but don't lend themselves to quantitative assessment in relation to other safety problems, or to prediction of crash outcomes (Phillips, 2014).

Fatigue and asleep-at-the-wheel seem to play their biggest roles in crashes resulting in the deaths of commercial drivers. In 1990, the U.S. National Transportation Safety Board studied 182 fatal-to-the-driver large truck crashes. Most were single-vehicle road departures. Their in-depth investigations revealed fatigue to be a principal cause in 31%, making it the biggest single factor in these crashes. NTSB's 31% statistic has important implications for HGV driver safety, but should not be generalized to larger crash populations such as all HGV crashes. Only about one in 700 U.S. large truck crashes is fatal to the truck driver, and the police-reported fatigue rate in these crashes is about 30 times that of all other large truck crashes (Knipling, 2009a).

Many factors affect fatigue crash percentages. Fatigue plays a bigger causal role, both relatively and absolutely, in large, sparsely populated countries like Australia. Of 461 serious large truck crashes investigated during 2011, fatigue was identified as the principal cause for 12%, making it second only to excessive speed (at 25%) as a crash cause (Driscoll, 2013).

When trucks and cars collide, which driver is more likely to be fatigued? One might suspect the truck driver, given their long driving hours and known health deficiencies. Yet U.S. studies clearly show the opposite. In LTCCS car-truck crashes, the car driver was nine times more likely than the truck driver to be asleep-at-the-wheel, and more than twice as likely to be labelled "fatigued" (Starnes, 2006). The U.S. National Motor Vehicle Crash Causation Study, using similar in-depth investigations, found car drivers to be asleep in 6% of 199 car-truck crashes, versus 0% for truck drivers. Fatigue was a contributing factor for 17% of the car drivers versus 2% of the truck drivers (Knipling, 2015c).

Little reliable information is available to quantify the role of fatigue in bus (motorcoach) crashes. In a small study applying LTCCS in-depth investigations to 39 bus crashes, none was attributed to asleep-at-the-wheel or driver fatigue (FMCSA, 2009a). The NTSB investigates severe, high-profile bus crashes in the U.S., and finds many are fatigue-related.

3. FATIGUE & DRIVER HEALTH

The health effects of reduced sleep may be less obvious than the performance effects, but they are probably equally important. Apart from the intrinsic value of health, poor worker health results in lower productivity and increased absenteeism. Poor driver health can degrade safety in various ways. It reduces driver performance, makes drivers vulnerable to medical crises like heart attacks, and over time leads to chronic conditions which shorten driver careers. When experienced commercial drivers retire in their 50s and early 60s, they are often replaced by younger, less experienced, higher-risk drivers. In addition to their greater overall risks, younger drivers are more likely to fall asleep at the wheel (Knipling, 2009a).

3.1 Health Status of Truck & Bus Drivers

Commercial drivers are among the unhealthiest of our citizens. Pathological health conditions and behaviors are far more prevalent among commercial drivers than the general population. In North America, direct and indirect driver medical costs are ever-increasing for transport companies and drivers themselves. The U.S. National Institute of Occupational Safety and Health conducted a nationally representative survey of long-haul truck driver health and injuries (Sieber et al., 2014). Researchers derived prevalence estimates for health conditions, injuries and work/sleep patterns, and compared them to the U.S. national working population. Comparative statistics included:

- Smoking: 51% of truck drivers versus 19% of the U.S. population
- Obese (Body-Mass Index $\geq$30): 69% vs. 31%
- Morbid obese (BMI $\geq$40): 17% vs. 7%
- Self-reported diabetes: 14% vs. 7%
- One major cardiovascular risk factor (hypertension, smoking, or obesity): 88% vs. 54%.
- All three risk factors: 9% vs. 2%.
- Not covered by health care plan or insurance: 38% vs. 17%.

Why are commercial drivers so unhealthy? The most obvious answer is the many *job-related* factors already cited. Yet there is compelling research suggesting that *non-job-related* factors also affect individuals' health status and behaviors. These include genetic predispositions, heath-related demographics, and social/family norms. Family and twin studies show, for example, that obesity and physical activity level have heritabilities in the range of 0.40 to 0.70 (O'Rahilly & Farooqi, 2008; Lightfoot, 2011). To the extent that such traits are heritable, their variations are predictable from *genetic* family relationships. Social norms within families and communities also strongly affect health behaviors and conditions apart from daily work conditions. The apparent role played by non-job factors suggests reciprocal causation between poor health and commercial driving. That is, obese and otherwise unhealthy people seem to self-select for the job (and its minimal physical demands), and then working on the job exacerbates their health problems.

3.2 Health Effects of Sleep Deprivation

Physiological effects of sleep restriction include increased blood pressure, increased heart disease, gastrointestinal problems, metabolic changes (potentially leading to diabetes), increased stress hormones, reduced immune response, increased sick days, increased calorie consumption, and weight gain. Sleep loss causes depletion of lepsin, the "satiety hormone." This results in overeating, increased blood sugar, and weight gain (Boivin, 2012). Psychological changes following sleep loss include irritability, disruption of relationships, worsened psychiatric conditions, and decreased quality of life (NAFMP, 2013). Recent research has further highlighted the many negative health effects of sleep loss, and the health benefits of good sleep. An endocrinology study from the Université Paris Descartes-Sorbonne Paris Cité (Faraut et al., 2015) has reported hormonal changes caused by sleep deprivation, as well as the mitigating benefits of napping on these hormonal changes. Eleven healthy men were permitted just two hours nightly sleep. This sleep deprivation caused a 2.5-fold increase in urinary norepinephrine as well as other endocrine changes indicative of stress. However, this increase in physiological stress was nullified when subjects were permitted two 30-minute naps during the day. Thus the benefits of napping include hormonal corrections as well as enhanced alertness and mood.

3.3 Obstructive Sleep Apnea (OSA)

An *apnea* is a stoppage of breathing lasting 10 seconds or more. In Obstructive Sleep Apnea (OSA), breathing stops repeatedly during sleep due to closures of the upper airway. Apnea rates of less than five per hour during sleep are considered normal, but higher rates characterize OSA. OSA severity is based on closure rate determined in an overnight sleep study. Apnea rates as high as 100 per hour can occur in severe OSA.

There are a number of distinctive risk factors and warning signs for OSA, as seen in the textbox. People often respond to poor sleep by increasing their sugar and calorie consumption; thus OSA tends to worsen obesity as well as being an effect of obesity. Studies of non-commercial drivers suggest a 2- to 7-fold increased OSA crash risk (Sassani et al., 2004). OSA can result in medical disqualification for commercial drivers, although it is often undiagnosed and undetected during the qualification process. An estimated 28% of U.S. commercial drivers have mild-to-severe OSA (Pack et al., 2002). A Finnish survey of 1,097 HGV drivers found that one fifth suffered from OSA (Partinen et al., 2005).

OSA Risk Factors & Indicators

- **Obese or overweight**
- **Male**
- **Age 40+**
- **Large neck size**
- **Recessed chin**
- **Small jaw**
- **Large overbite**
- **Family history**
- **Snoring (especially if irregular)**
- **Daytime sleepiness**
- **High blood pressure**
- **Diabetes.**

Source: NAFMP (2013)

A recent case-control study in Western Australia compared 100 long-haul heavy vehicle drivers who were involved in police-reported crashes to non-involved drivers recruited from area truck stops (Meuleners et al., 2015). Driver interviews included a diagnostic OSA questionnaire. Heavy vehicle drivers with OSA profiles were more than three times more likely (Adjusted Odds

Ratio = 3.42; 95% Confidence Interval 1.34 to 8.72) to be involved in a crash than were controls. Drivers who had not received any fatigue education were also highly overinvolved in crashes. Other crash risk factors included depression, young age (<35), a previous crash, obesity, and lack of regular exercise.

4. FACTORS AFFECTING ALERTNESS & FATIGUE

Two general categories of fatigue causes are internal physiological factors and task-related factors (Thiffault, 2011). Internal physiological factors can be further classified as individual differences in susceptibility and temporal factors. Thus, a taxonomy of factors affecting fatigue and alertness include:

- Individual differences in fatigue susceptibility, which may be related to sleep disorders, other medical conditions, or physiological variability;
- Temporal physiological factors affecting all people daily:
  - Circadian rhythms (time-of-day)
  - Amount of recent sleep, including primary sleep periods and naps.
  - Sleep inertia; i.e., grogginess experienced upon awakening.
  - Time awake since last principal sleep.
- Task and environmental factors.

4.1 Individual Differences in Susceptibility

Individual susceptibility to drowsiness varies widely. The large U.S./Canada *Driver Fatigue and Alertness Study* (Wylie et al., 1996) was among the earliest naturalistic studies employing in-vehicle cameras looking at the drivers' faces. Video reviews found that that 54% of all the drowsy episodes were experienced by just 14% of the drivers in the study. Experimental laboratory studies of young, healthy subjects show wide individual differences in alertness and performance in response to sleep deprivation. Moreover, distinctive individual differences are reliable and repeatable in separate sleep deprivation sessions conducted months apart (Dinges et al., 1998). This suggests that fatigue susceptibility is an enduring personal trait much like personality or athletic ability, and with a similar genetic influence (Van Dongen et al., 2004; 2005). Martin Moore-Ede (1993, 2007) has used the term *chronotype* to refer to each individual's fatigue susceptibility and other alertness-related idiosyncrasies such as "morningness" vs. "eveningness" and propensity for napping. Genetic variation, medical conditions, and engrained personal habits all play a role in differentiating chronotypes.

4.2 Temporal Physiological Factors

4.2.1 Time-of-Day and Circadian Rhythms

Much of the daily variation in human alertness can be modeled based on three main temporal factors operating daily and reflecting physiological processes. They are recent sleep, time-of-day (circadian rhythms), and time awake (Rosekind, 2005). Of these, time-of-day is probably the "strongest and most consistent factor." (Wylie et al., 1996). Drowsiness is far more likely to be seen during overnight and early morning hours than during daytime. This effect is partly due to the effects of light and dark, and to the usual timing of sleep. The strongest source, however, is the endogenous 24-hour pacemaker known as the *circadian rhythm*. People or animals locked in windowless laboratories continue indefinitely to show regular daily cycles of metabolic, hormonal, physical, and mental activity. The Suprachiasmatic Nuclei of the hypothalamus has been identified as the controlling brain structure. Figure 3 below approximates arousal levels resulting from the circadian rhythm. For most people, the best predictor of driving alertness at any given time is their circadian status.

A person's likelihood of falling asleep-at-the-wheel is approximately inversely related to circadian arousal. One small discrepancy is notable. The typical circadian low is at about 4:00am, whereas that the biggest fatigue crash risk seems to occur at between 5:00 and 7:00am. This difference may occur because all-night drivers struggle through their circadian lows but still "lose the fight" later before full alertness occurs.

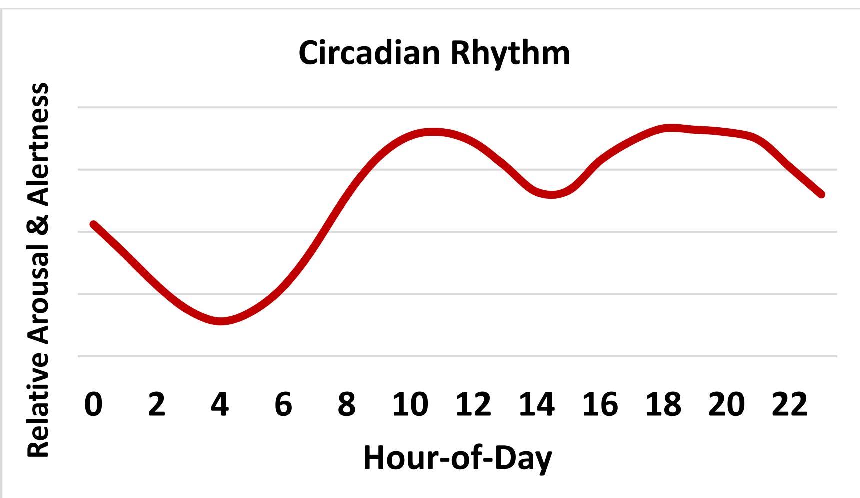

Figure 3. Approximate circadian arousal and alertness levels. **Knipling, 2009a**

4.2.2 Amount of Sleep

Sufficient sleep is necessary for both alertness and health. Sleep deficiencies may be acute (e.g., over a 24-hour period) or chronic, reflecting enduring bad personal habits and/or medical conditions. One night of reduced sleep typically results in small, perhaps subtle effects. Multiple nights cause cumulative decrements, while longer-term reduced sleep seriously impairs both performance and health. Many people who claim they function maximally on reduced sleep have really just become accustomed to their own reduced maximum levels.

A laboratory sleep deprivation study by the U.S. Walter Reed Army Institute of Research (Balkin et al., 2000) compared professional driver subjects allowed 9, 7, 5, or 3 hours in bed nightly. Over eight days of testing, 9 hours sustained maximum performance while 7 hours caused small deficits on some measures. Five (5) hours caused increasing day-to-day declines, while limiting sleep to just 3 hours reduced performance profoundly and cumulatively. Figure 4 below shows these results. Not shown are recovery periods after the eight days of sleep deprivation. Several days of full sleep were required before impaired drivers "repaid their sleep debts" and recovered full performance.

Fatigue-related crashes are usually associated with insufficient sleep prior to the crash. In Australia, Arnold and Hartley (1998) found that truck drivers who had had less than 6 hours sleep were three times more likely to have a hazardous incident and 2.5 times more likely to fall asleep at the wheel. LTCCS drivers in single-vehicle crashes were more than twice as likely to have had insufficient sleep than those in multi-vehicle crashes. Single-vehicle crashes are well known to have higher fatigue involvement than multi-vehicle crashes (Knipling, 2009a, b).

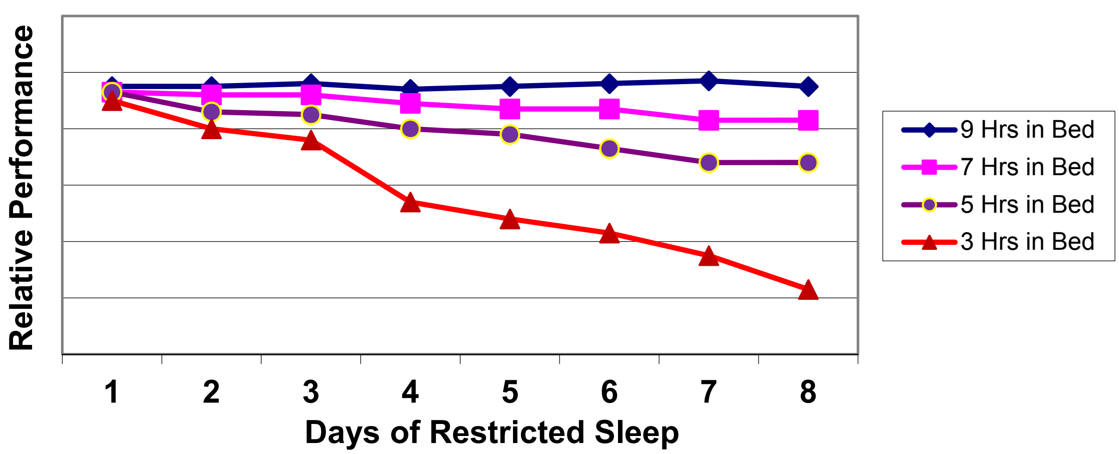

Figure 4. Performance (vigilance) declines over successive days of sleep restriction. **Balkin et al., 2000.**

4.2.3 Sleep Inertia

Sleep inertia is the transient grogginess felt upon awakening, especially when from a deep sleep. It can last 20 minutes or more. Sleep inertia can affect driving, especially in the early morning hours when circadian arousal is lowest. Caffeine is a common, effective countermeasure. Some sleep-performance models consider sleep inertia as a secondary predictor variable.

4.2.4 Time Awake

Time awake is well established as a physiological factor in alertness, and is an element in many Sleep Performance Models (Krueger, 2004). In almost any driving schedule, time-on-task (i.e., driving hours, working hours) co-varies with time awake to a high degree. Few driving studies have clearly distinguished time awake effects from time-on-task effects, but it is likely that time awake is the more operative factor. For most people on most days, the steepest decline in daily alertness occurs after about 16 hours of wakefulness, and relatively independently of driving or other specific activities (Rosekind, 2005, Dawson et al., 2011).

In 2004 the U.S. implemented a new HoW rule limiting most HGV driver daily duty periods to 14 hours of elapsed time. In other words, the daily tour-of-duty was limited to 14 hours, regardless of activities within that period. This rule was warranted in light of the natural daily falloff of alertness after 16 hours. Some U.S. transit bus operators work daily split shifts with driving periods in the morning and evening, spanning up to 16 hours of elapsed time. Drivers' commutes and other necessary personal activities contribute to extend daily wakefulness well above 16 hours and to restrict nightly sleep periods. This schedule has been found to create chronic fatigue and increased crash risk (Sando et al., 2011).

4.2.5 "Bathtub" Sleep-Performance Model

A simple but elegant conception of temporal changes in alertness is seen in the "bathtub" model shown below. Alertness level is represented by the amount of water in the bathtub. Circadian highs (late morning, early evening) fill the bathtub, while circadian lows (especially early morning) and time awake (especially 16+ hours) drain it. Different people may have different bathtub capacities and designs – some fill more easily while others drain more easily.

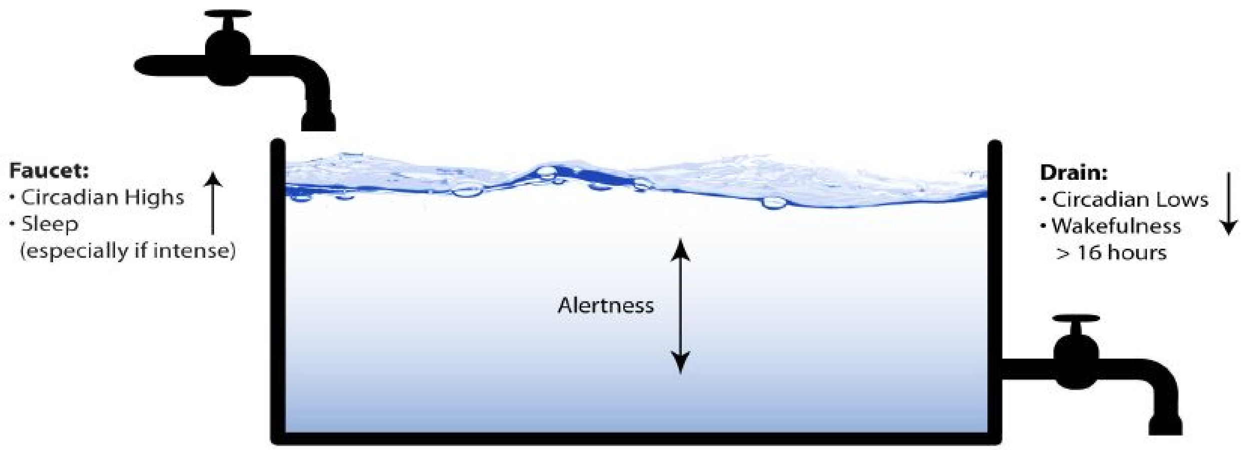

Figure 5. "Bathtub" model of alertness showing action of three principal temporal physiological factors.

4.3 Task & Environmental Factors

4.3.1 Time-on-Task (Hours Working/Driving)

Sharp time-on-task declines in performance occur during intense tasks such as reaction time tests. But driving is not typically an intense task, and no similar time-on-task effects on driving performance are seen. In two large studies (Jovanis et al., 2011; Blanco et al., 2001), the U.S. DOT reported increases in crash and naturalistic driving safety-critical events associated with hours of driving and work. Yet both reported studies had significant scientific deficiencies (Knipling, 2015). Neither study controlled for confounding factors including time-of-day, traffic density, or roadway type. Neither analysed its events (crashes for Jovanis, SCEs for Blanco) to identify the presence of driver fatigue or any kind of driver error. In the Driver Fatigue and Alertness Study (Wylie et al., 1996), another large DOT-sponsored study which did measure driver fatigue, time-on-task was not a strong or consistent predictor of fatigue. In the LTCCS, no associations were seen between time-on-task (hours driving and hours working) with the relative rates of crash categories known to differ greatly in fatigue incidence. Crash category associations *were* seen with known physiological factors including hours of sleep and time-of-day (Knipling, 2009b). Time-on-task may be a true, independent factor in driver alertness and safety, but clearly it is weaker than major physiological factors.

One would expect alertness and performance to often decline over the course of multiple work shifts since many drivers do not get sufficient sleep between shifts. The Balkin et al. (2000) sleep deprivation study described earlier (see Figure 4) suggests that driver performance might decline within each work week. Field evidence on this is mixed, however (Knipling, 2009a).

Excessive personal activities on weekends sometimes results in drivers being more fatigued at the beginning of their work weeks than at the end (NAFMP, 2013).

4.3.2 Task Difficulty and Monotony

The relation of task complexity to performance is well-known as an inverted "U." That is, performance is likely to be low for monotonous, unstimulating tasks, rise to an optimal level for moderate-complexity tasks, and then fall for highly complex tasks. The two extremes may be labeled "underload" and "overload" (Shinar, 2007; Phillips, 2014). Underload characterizes much of long-distance driving, and is the greater threat for drowsiness. Tolerance for monotonous driving may be related to personality. In a simulator study, Thiffault and Bergerson (2003) found that sensation-seeking people (who were generally also extraverts) were more vulnerable to alertness loss from the monotony of long and boring driving trips. It is believed that such individuals have less endogenous stimulation keeping them awake.

4.3.3 Other Environmental Factors

Environmental factors also affect alertness. These include road conditions, weather, environmental stress (such as heat, noise, and vibration), vehicle design, light and dark, and other stimulation. Moore-Ede (1993) called them alertness "switches" – factors that can wake you up or make you sleepy. Social interaction is a strong alertness switch. Interacting with others, especially in-person, has a strong alerting effect. Talking on a mobile phone or two-way radio is well-known as a fatigue countermeasure used by drivers. A companion risk, though, is distraction. Team drivers generally experience less drowsiness than do solo drivers, in part due to their social rather than solitary work environment (Knipling, 2009a).

5. FATIGUE COUNTERMEASURES

An array of interventions are available to counter fatigue, beginning with mandatory HoW rules. Other countermeasures include fatigue risk management systems, technologies, and various policy and management practices.

5.1 Hours-of-Work (HoW) Rules

HoW rules for HGV drivers are necessary to "level the playing field" and prevent egregious abuses by some carriers and drivers. HoW rules contain numerous specific provisions to ensure reasonable driver schedules. These include minimum daily off-duty hours, maximum daily driving hours, maximum daily tour-of-duty (elapsed time), required breaks from driving, weekly maximum work hours, restart (i.e., 34-hour restart in the U.S.) provisions after time off, and sleeper berth use (including "split sleep" provisions). Governments base their HoW rules primarily on their believed effects on driver alertness, but there are inherent differences between the actual factors affecting alertness and HoW parameters. Table 2 below presents two lists. The first column shows various physiological and task-related factors that can affect driver alertness and performance. The second column lists HoW parameters. In some cases, there are clear and direct linkages; e.g., time-on-task and maximum daily driving hours. In other cases, the relationship is clear but indirect. For example, recent sleep is a prime physiological fatigue factor, but is regulated indirectly by HOS rules requiring sufficient time off to afford the *opportunity* for sufficient sleep. Some major fatigue causes are not addressed by HOS rules. These include individual differences in fatigue susceptibility and time-of-day. Both have large effects on driver alertness, but cannot be easily addressed through HoW rules. The imperfect alignment of human fatigue factors and HoW parameters is seen in various research results. For example, the Driver Fatigue and Alertness Study (Wylie et al., 1996) found significant alertness effects from amount of sleep and time awake, but not from time-on-task (hours driving).

Table 2. Human Alertness/Fatigue Factors and HOS Parameters

Factors in Alertness and Fatigue	HoW Parameters
Individual differences in fatigue susceptibility	Minimum daily off-duty hours
Circadian status	Maximum daily driving hours
Recent sleep	Maximum tour-of-duty
Sleep recency (sleep inertia)	Maximum daily work hours
Time awake	Schedule regularity (a product of compliance with other provisions)
General health and wellness	Weekly maximum work hours
Caffeine (or other stimulant) intake.	Restart (i.e., 34-hour restart in the U.S.)
Prescription and over-the-counter drug use	Breaks from driving
Alcohol and other recreational drugs	Sleeper berth use (including “split sleep” provisions)
Light/dark	
Time-on-task (hours driving or working)	
Task complexity	
Task monotony	
Ambient temperature	
Sounds and noises	
Social interaction	
Certain aromas	

Whatever the effects of HoW rules, one would expect them to be greatest for fatigue-specific (e.g., asleep-at-the-wheel) crashes or other indicators, and much less for broader crash categories or risk indicators. Motor vehicle crash rates reflect numerous interacting factors, most of which are not discernably related to fatigue. Figure 6 shows the “challenge” faced by HoW rules in affecting HGV crash rates. HoW rules have undeniable effects on driver fatigue but, whatever those effects, they are greatly muted in relation to all HGV crashes because of the many other “competing” crash factors. This includes road risks (e.g., traffic), the errors of other motorists which precipitate so many HGV crashes, and those errors of HGV drivers which are not closely related to fatigue, most notably excessive speed for conditions and distraction. Thus, effects of specific HoW rules on the overall HGV crash picture are likely to be limited.

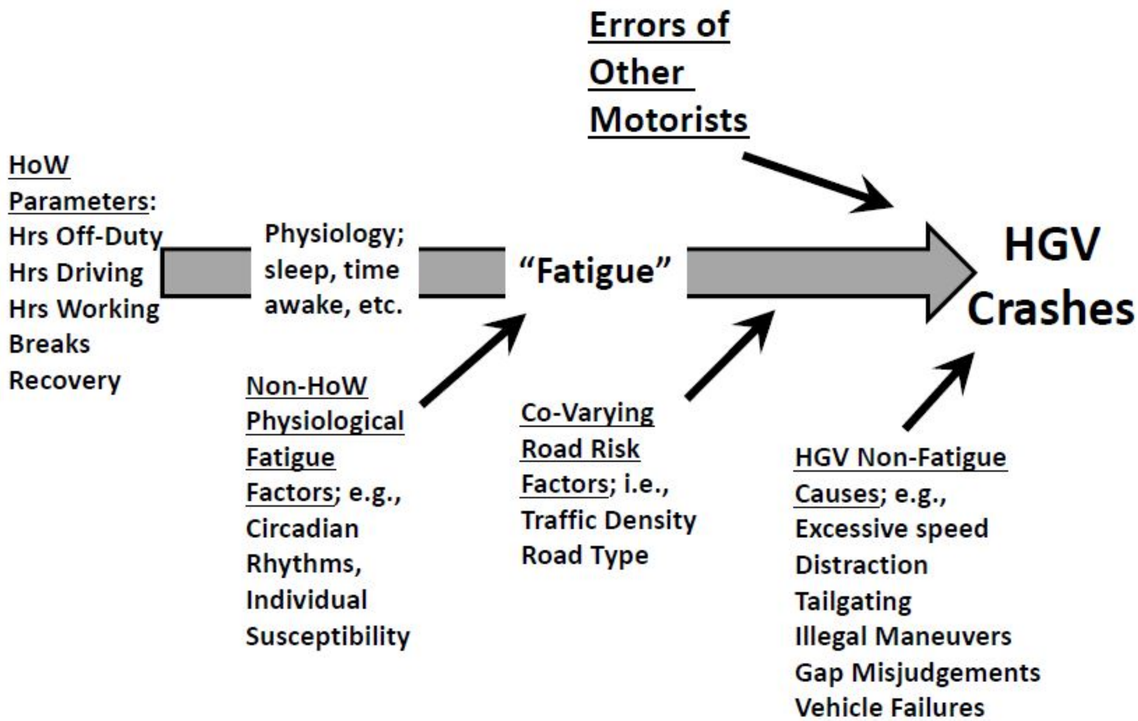

Figure 6. Potential "competing" factors in HoW effects on HGV crash rates. **Knipling 2015.**

5.2 Fatigue Risk Management Systems

The ETSC (2011) has noted that HoW rules "are simplistic and do not give due consideration to the range of factors . . . [suggesting the need for] "a more systematic approach." A Fatigue Risk Management System (FRMS) is an "explicit and comprehensive process for measuring, mitigating and managing" actual fatigue risks to both safety and health (Fourie et al., 2010). FRMSs treat fatigue as an ever-present risk to be addressed systematically in safety risk management (Phillips, 2014). FRMS elements include an organizational fatigue management policy, risk management procedures, a process for employees to report fatigue to management, a process for investigating the role of fatigue in accidents, fatigue education and training, and gap analysis of organizational goals vs. current status.

The North American Fatigue Management Program (NAFMP, *www.nafmp.com*) is a joint U.S./Canada venture to help transport companies manage driver fatigue proactively and "beyond compliance." The program includes online and carrier-taught classroom education for drivers, drivers' families, executives, managers, dispatchers, and shippers/receivers. Program content includes basic instruction on sleep and alertness, health and wellness, and sleep disorder screening and treatment. The NAFMP has been endorsed by both the U.S. National Transportation Safety Board (NTSB) and the American Trucking Associations (ATA), a leading trade association. In Europe, the German Social Accident Insurance Institution for the transport industry offers similar driver fatigue management awareness training in its program called “Keep awake behind the steering wheel” or “Wach am Steuer” (ETSC, 2011)

5.3 Fatigue Management Technologies

Fatigue management technologies can be specific to fatigue, or can prevent crashes more generally, including those caused by fatigue. Several non-specific technologies are probably more mature and effective at this time. Most notable are Lane Departure Warning (LDW) systems. LDW systems warn drivers as they begin to drift of out of their lanes, functioning like an in-vehicle rumble strip. In drowsiness, lane tracking deterioration usually begins well before lane edge crossings. LDW systems are potentially capable of providing corrective feedback to drivers well before they are imminent danger. Yet most current systems base driver feedback only on imminent or actual lane breaks. The provision of LDW system feedback to drivers during their early, incipient performance deterioration is an application which should receive greater research and development attention. The U.S. Insurance Institute for Highway Safety (Jermakian, 2010) has estimated that LDW systems on large trucks could prevent about 7% of fatal crashes. Because of the high mileage exposures of HGVs, their lifetime likelihoods of involvement in lane departure crashes are several times those of passenger vehicles. Crash severities are likely to be higher too. These factors combine to make countermeasure benefits-per-unit-cost far greater for long-haul HGVs than for passenger cars (Knipling, 2009a). FMCSA (2009b) has estimated the HGV LDW system return-on-investment to be 137% to 655% over five years, depending on risk exposure. Several other collision avoidance systems are effective though not specific to fatigue. They include Electronic Stability Control, Forward Collision Warning, and Side-Object Detection systems.

There are also several promising fatigue-specific approaches. In-vehicle *alertness monitoring* can be based on driver lane-keeping, on eyelid droop (e.g., PERCLOS), steering reversals, other physiological or performance measures, and/or by multiple measures combined into a single optimized assessment. Early proof-of-concept was provided in the 1990s by driving simulator studies showing concurrent PERCLOS and driver performance changes as drivers became drowsy (Wierwille, 1999; Knipling and Wierwille, 1994). Alertness monitoring is potentially a stronger countermeasure to HGV driver fatigue than electronic logging of HoW compliance because it would measure drowsiness and performance, not just weak correlates like driving time (Knipling, 2009a). Future carrier management and government regulation of commercial driver alertness and fatigue may be based on in-vehicle alertness monitoring.

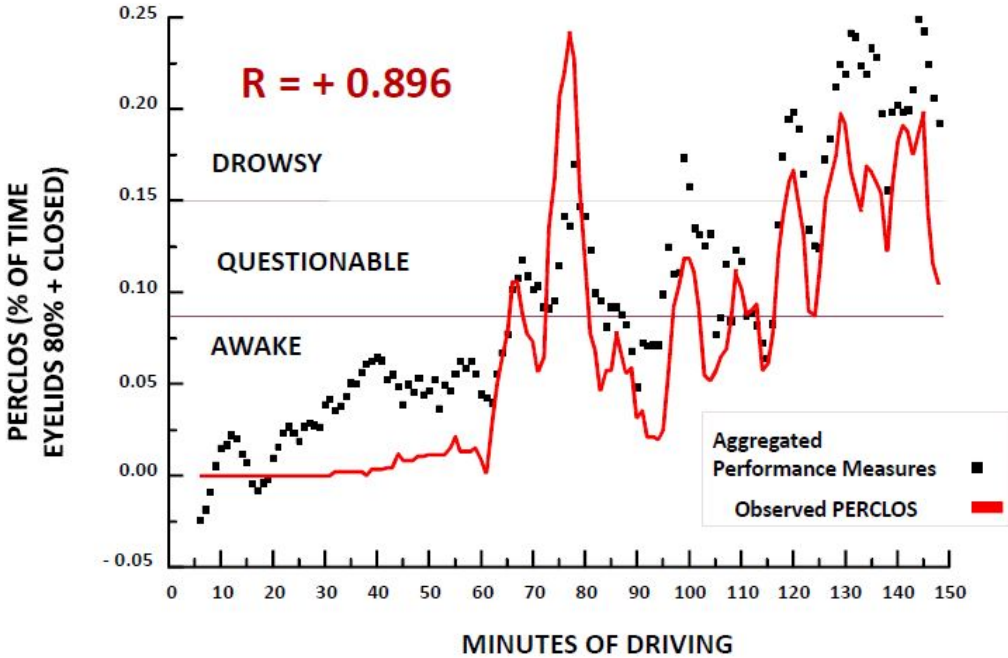

Figure 7. Concurrent, correlated changes in driving performance (mostly lane tracking measures) and eyelid closure (PERCLOS) for a sleep-deprived driver. **Knipling and Wierwille, 1994.**

Fatigue management technologies include personal monitoring and testing devices. Activity watches such as the Fatigue Science *Readiband*® and even the popular *Fitbit*® can estimate sleep quantity and quality. From this one can assess or predict likely alertness. Another approach might medical, polysomnographic (e.g., electroencephalographic) or psychomotor tests of personal fatigue susceptibility. Such tests, if valid, would help screen out high-fatigue-risk drivers before they are ever hired to drive HGVs.

5.4 Policy & Management Changes

Governments can be expected to continue to revise HoW rules and driver medical qualifications, such as those relating to obesity and OSA. More rigorous health requirements for HGV drivers may most effectively reduce risks. Other changes to laws, policies, regulations, and practices may also contribute. Interventions may include regulations to reduce loading and unloading delays, known as *driver detention* in North America. The U.S. Government Accountability Office (2011) found that 68% of surveyed drivers had been detained for more than two hours at some time in the past month. Of drivers detained, 80% said it affected their HoW compliance, 65% lost revenue, but only 35% were compensated financially. Most U.S. long-haul drivers are paid by distance driven, not by the hour. Many drivers are never compensated for time delays. HGV are too often the “elastic band in the supply chain link,” repeatedly stretched to accommodate system inefficiencies (NAFMP, 2013).

Australia has formalized "Chain of Responsibility" rules to extend accountability and liability to all parties who might bear responsibility for safety breaches, including shippers and receivers placing unrealistic demands on drivers (Moore, 2007; Quinlan, 2008). An EU regulation requires that consignors, freight forwarders, tour operators, principal contractors, sub-contractors and driver employment agencies ensure that contractually agreed transport time schedules comply with drivers' HoW rules. Enforcement of such worker protections is problematic, however, due to the difficulty of identifying and prosecuting violators (ETSC, 2011).

Many advanced nations have serious shortages of rest parking space for commercial vehicles. The U.S. Wall Street Journal (Morris, 2015) reported an online survey of 4,000 truck drivers finding that nearly 40% spent an hour or more daily finding rest parking. About 28% often park on freeway ramps; 52% behind shopping centers, and 45% in vacant petrol stations or strip malls. In Europe, studies have identified a shortfall of approximately 50,000 HGV parking spaces, with the largest deficits in Germany, France, Austria, Sweden and Spain (Journé, 2009). The ETSC (2011) has recommended that EU member states' planning processes include provisions for secure truck parking facilities along major transport corridors.

Proactive operational planning of parking stops by companies can reduce fatigue. In the U.K., Suckling Transport recognized that its trip and route planning needed to go beyond basic route selection to consider safe locations for driver rest. Their managers identified and prescribed safe parking locations for driver breaks, and then monitored drivers to ensure that drivers were compliant (ETSC, 2011).

One sees multifaceted fatigue countermeasures applied at the levels of governments, carriers, drivers, vehicles, and roadway environments. At their best they are grounded in the physiology of sleep and supportive of holistic driver health and wellness.

6. CONCLUSIONS & RECOMMENDATIONS

6.1 Personal Behaviors

Driver education emphasizes holistic personal wellness in five areas: diet, exercise, sleep, other positive behaviors (like not smoking), and positive relationships. *Sleep hygiene* refers to personal behaviors supportive of sound sleep and high alertness. People should plan their daily lives to be consistent with good hygiene, and work to develop strong, positive health habits. These include (Knipling, 2009a; NAFMP, 2013):

1. Generally, sleep as much as possible. This includes getting extra sleep on weekends. (Caveat: a few psychological and medical conditions involve excessive sleep.)
2. Wake up naturally. Set alarms only when essential.
3. Plan for sleep inertia upon awakening. Avoid driving for 30-60 minutes and, for most people, until after a cup of tea or coffee.

4. Take a short nap daily. The optimal nap time is 20-30 minutes for most people. Take longer naps only when preparing for shift changes; e.g., day-to-night.
5. Take breaks from driving. Breaks with a nap are best. Caffeine, bright lights, fresh air, social interaction, and exercise can also be helpful.
6. Plan for circadian variations in alertness. Low periods are best for naps.
7. Keep a regular schedule. When schedules must change, forward rotation (starting later) is better than backward rotation (starting earlier).
8. Use dark and light. Dark promotes sleep while light promotes wakefulness.
9. Relax before bedtime. If possible, lower overhead lights. Avoid computers.
10. Self-assess drowsiness based on objective signs. Subjective self-assessment is unreliable. Focus on objective signs like eyelid droop, disjointed or wandering thoughts, microsleeps, head bobbing (loss of muscle tone in neck), weaving in the lane, and "drift & jerk" steering.
11. Monitor yourself for signs of chronic sleep deprivation. These include falling asleep very quickly at bedtime, dozing in front of the TV, falling asleep at red traffic lights, or falling asleep after a big meal or when bored.
12. Use caffeine strategically. While not a substitute for sleep, caffeine does help sustain alertness when used prudently.
13. Avoid alcohol before bedtime. Alcohol makes you sleepy but disrupts sleep later.
14. Exercise regularly but not within 2-3 hours of bedtime.
15. Lose weight if you are overweight.
16. Try to assess your personal risk. The large individual differences in susceptibility to drowsiness tend to endure over time. A history of drowsiness while driving or symptoms of chronic sleep deprivation mean you are also at future risk.
17. Wear safety belts. Fatigue crashes often result in high-speed impacts and/or rollovers, crash types where safety belt use is most critical.

6.2 Organizational Policies & Practices

Transport companies and other organizations should first do all they can to encourage positive sleep hygiene behaviors by their drivers and other employees. In some cases (e.g., safety belt use), correct behaviors can be required. Organizations can:

1. Ensure that one or more top managers becomes a fatigue management expert and mentor to drivers and other employees.
2. Consider HoW and other legally required fatigue-management practices to be "necessary but not sufficient."
3. Recognize the limitations of HoW rules, but still enforce compliance with those rules. Compliance does not guarantee alertness, but *non*-compliance does suggest a driver at-risk for fatigue and at-risk generally.
4. Include written guidelines on both HoW compliance and the importance of "beyond compliance" strategies (e.g., education) in organizational policy handbooks.

5. Make work schedules as regular as possible, while still allowing flexibility and worker choices.
6. When schedule changes are needed, notify drivers in advance, and rotate schedules forward.
7. Screen drivers for OSA and other sleep disorders.
8. Facilitate and monitor OSA treatments, such as CPAP use.
9. Carefully consider overall operational schedule strategies. For example, night driving *may* be safer than day driving overall, but it requires more active fatigue management.
10. Empower drivers to stop for naps and other rest when they feel they need it.
11. Compensate drivers for uncontrollable delays; e.g., excessive detention time, force majeure.
12. Consider the advantages of driver teams over solo drivers for long hauls. Teams appear to be generally safer.
13. When evaluating drivers, whether they are prospective or current employees, look for signs of chronic sleepiness or past involvements in fatigue-related incidents. Involvement in single-vehicle crashes is one indicator of risk.
14. Focus intensified efforts on known or suspected high-fatigue-risk drivers. One-half or more of a fleet's total fatigue crash risk probably resides in 10-20% of its drivers.
15. Beware of drivers with lengthy commutes. A one-hour commute effectively adds two hours to each work day and raises the risks of chronic sleep deprivation. Similarly, beware of drivers who "moonlight" at other jobs.
16. Implement both fatigue and total health/wellness education for employees. Various online and other packaged programs are available. Maintain careful records and high instructional standards.
17. Involve driver spouses and other family members in fatigue/health education. Health behaviors, both good and bad, "run in families."
18. In long-haul fleets especially, adopt vehicle-based safety technologies such as Lane Departure Warning and Forward Collision Warning. Consider driver alertness monitoring technologies as well.
19. Publicize company fatigue/health programs and expectations in driver recruiting programs. This will help attract safety- and health-conscious drivers while also subtly discouraging unhealthy ones.

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