

## **Pilot study and cumulative risk framework to advance long-haul driver health**

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### **Abstract**

Commercial drivers are essential to the economic recovery, yet their work exposes them to many health and safety hazards. Research to improve driver health should be designed with an understanding of both the complex occupational environment and the risk management context. We present results from a small pilot study of driver health concerns and behaviors to illustrate concepts and frameworks from human health risk assessment and management that may assist in the design and translation of driver and other worker health research. The pilot study surveyed 18 long-haul truck drivers at a truck stop using an instrument adapted from the International Physical Activity Questionnaire and a transient community needs assessment developed for the US Antarctic Program Recreation and Wellness Survey. Respondents' characteristics and health concerns reflect existing literature: mostly male of older age with musculoskeletal and chronic health conditions. The two most common barriers to physical activity were lack of time and physical limitations. Applying cumulative risk assessment and risk-based decision-making frameworks, we suggest that preventive health management opportunities can be improved for these transient workers through actions of employers, truck stop owners and their communities. Considering lessons learned in implementing the pilot, cumulative risk assessment, and risk-based decision making in research design can facilitate holistic research considering co-exposures, risk factors and mitigators across multiple domains of health to inform worker protection.

**Keywords:** cumulative risk assessment, drivers, physical activity, research translation, risk management

Truck drivers have been considered essential workers during the pandemic and will continue to be essential to the nation's economic recovery (Cybersecurity & Infrastructure Security, 2020). Long-haul drivers have a challenging work environment that is sedentary and stressful (Lemke et al., 2020). Due to the itinerant nature of the work drivers spend extended periods away from families and home communities. They face increased risk of various health outcomes, for example: increased risk for cardio-metabolic diseases and related risk factors of obesity, high blood pressure and metabolic syndrome; it is an aging workforce with high rates of injury; and time pressures, shift work, poor sleep and isolation can contribute to work stress, poorer mental health and inadequate work-life balance (Hege et al., 2018; Lemke et al., 2017; Thiese et al., 2015; Combs et al., 2018; Newnam et al., 2020; Apostolopoulos et al., 2016; Garbarino et al., 2018; Hege et al., 2019).

Our reliance on long-haul drivers is great but our understanding of their complex occupational health challenges is limited. A review of occupational health research focused on combined or co-exposure interactions found no studies of drivers (Fox et al., 2021). Lemke et al. raised a related concern in their commentary about long-haul drivers and COVID-19, stressing the need to consider a syndemic approach to health research so that studies related to the pandemic would be done with the context and understanding of the stressogenic and obesogenic nature of the occupation (Lemke et al., 2020). "Syndemics are characterized by biological and social interactions between conditions and states, interactions that increase a person's susceptibility to harm or worsen their health outcomes" (Horton, 2020). The concept of syndemics aligns with cumulative risk assessment, an area of environmental and occupational health research and practice. Cumulative risk assessment is "an analysis, characterization, and possible quantification of the combined risks to health or the environment from multiple agents or stressors" (U.S. EPA, 2003). Like syndemics, cumulative risk assessment is concerned with health effects of multiple stressors (biological, chemical, physical, psychosocial) acting together (Abt et al., 2010). Using a cumulative risk framework may help design a syndemic approach to research thereby providing a more holistic understanding of exposures and risks and potentially multiple options for intervention.

Drivers as an occupational group make a compelling case for applying a syndemic lens but health research in any work context may benefit. This report: 1) describes the methods, implementation and lessons learned from the pilot work; 2) uses descriptive results from the pilot to illustrate exposures and health concerns within a cumulative risk assessment conceptual framework; and 3) discusses how

the framework may assist in the design and translation of health research.

The pilot study was motivated by an interest in exploring truck stops as temporary communities where the "residents" are a constantly changing group of drivers seeking access and use of health-promoting facilities and services. The pilot study tested a survey instrument and research protocol. We present below a descriptive summary of selected results along with lessons learned about the approach to guide future efforts. We then use the descriptive results to inform a discussion of cumulative risk assessment and risk-based decision making as aids to operationalize and translate syndemic research.

### **Pilot Study Methods**

The pilot study was conducted by the Texas A&M Transportation Institute in partnership with Dr. Teresa Penbrooke of GreenPlay Research, Education and Development (GP RED) and BerryDunn. Investigators surveyed long-haul truck drivers at a truck stop (Farzaneh et al., 2018). The survey instrument ("Trucker Health Questionnaire") was developed using items from the validated and widely used International Physical Activity Questionnaire (IPAQ) and a transient community needs assessment initially developed for the US Antarctic Program Recreation and Wellness Survey (Penbrooke, 2010). The instrument included items on demographics; physical activity and time spent sitting; recreation and leisure activities; interest in food and nutrition; and environmental and other health concerns. The instrument had a total of 46 items and required at least 30 minutes to complete. The survey was available in hardcopy and on a tablet computer. The Institutional Review Board at Texas A&M University approved this work. The truck stop location that hosted the pilot study was located along I-35 and had 200 truck parking spots; this truck stop had participated in a previous study. It had several health-promoting features including indoor and outdoor fitness facilities and opportunities for improved nutrition, such as healthy restaurant choices. Four trained study staff gathered data over a 3-day period in December 2018.

### **Pilot Study Results**

A convenience sample of eighteen participants completed the study (see Table 1). The participants were predominantly male (n=16) and ranged in age from 18 to 65+ years (average = 49 years). Years of work as a driver varied, from less than 1 year to more than 20 years of experience. The driver respondents reported higher than average hours of sitting per day, with 12.4 hours on weekdays and 11.7 hours on weekends. On average in the U.S., adults are sedentary 7.7 hours per day (Ussery et al., 2018).

Table 1. Participant characteristics

	Number (% or Range)
Total Participants	18 (100%)
Male	16 (89%)
Female	2 (11%)
Average Age (years)	49 (Range: 18 to over 65)
Years a Driver*	
<1	1 (6%)
1 to 3	4 (23%)
4 to 10	2 (12%)
>10	2 (12%)
>20	8 (47%)
Daily hours of sitting	
Weekday Average	12.4 (Range: 2 to 24)
Weekend Average	11.7 (Range: 2 to 24)

\*One participant chose not to answer.

Most participants (60% to 90%) reported not engaging in job-related or leisure-time walking or moderate or vigorous activity (see Table 2). Participants reporting walking or moderate or vigorous activity exceeded the recommended 150 minutes per week on average (U.S.

Department of Health and Human Services, 2018). One participant reported only 120 minutes per week of moderate leisure activity, but this participant also reported moderate job-related activity. Most participants reporting an activity reported more than one.

Table 2. Participant physical activity

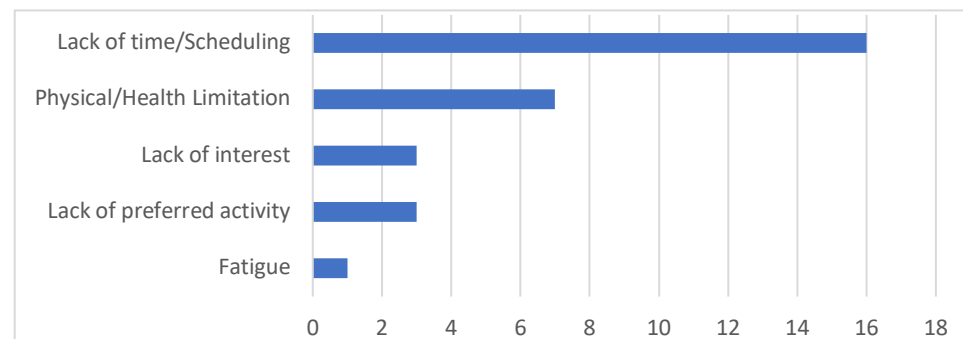
Activity Type	Did not do activity (%)	Did Activity (%)	Minutes/week Avg (Range)
Job-related walking	n=12 (67%)	n=6 (33%)	553 (60-2100)
Leisure walking	n=13 (72%)	n=5 (28%)	375 (315-480)
Job-related moderate	n=11 (61%)	n=7 (39%)	718 (60-3360)
Leisure moderate*	n=16 (89%)	n=1 (6%)	120
Job-related vigorous	n=12 (67%)	n=6 (33%)	650 (360-1260)
Leisure vigorous*	n=12 (67%)	n=4 (22%)	446 (105-1260)

\*Participant(s) chose not to answer.

Participants also reported barriers to physical activity or recreation (more than one could be reported), as shown in Figure 1. Too little time or a scheduling issue was the most

common barrier (n=16), followed by a physical or health limitation (n=7), lack of interest (n=3), lack of preferred activity (n=3), and fatigue (n=1).

Figure 1. Reported barriers to physical activity



Health conditions or concerns reported included back issues (n=4), diabetes (n=3), concern about exhaust fume exposure (n=2), overweight (n=1), cancer (n=1), neck injury (n=1), heart problem (n=1), and sleep apnea (n=1). Regarding intention to practice healthy eating, about half of respondents reported trying to do this “to a great extent” (n=8), one-third of them reported trying to do this “to a small extent” (n=6), and one reported no interest. Specific

reasons for choosing the truck stop included: handicapped parking; smoking area; availability of a weight room and exercise equipment; availability of a variety of activities; and availability of healthier foods. Respondents also reported interest in playing basketball (not available at the stop) and the need for better walking trails.

#### Lessons learned from pilot study

The research area has potential. Most participants did not engage in physical activity at the recommended level; however, they did report the intention to practice healthy eating and availability of activities was among the reasons for choosing the truck stop. The approach was successfully implemented, but important challenges included recruiting truck stop locations, scouting of locations for volume of traffic, enrolling drivers, and design and implementation of

the survey. The main lessons learned indicate that several enhancements are needed in advance of further work particularly in identifying and characterizing host truck stops, enhanced training on participant engagement, and shortening the survey to reduce respondent burden. The results also suggest that understanding drivers' interests could be helpful to truck stop owners in developing services and facilities that could attract additional business. Further details are presented in Table 3.

Table 3. Challenges and lessons learned during pilot study implementation

Challenge	Pilot study experience	Lesson learned
Identify/recruit truck stops to host the study	Recruiting truck stops proved difficult and no new truck stops were identified. The host stop had been involved in a previous research effort.	Outreach efforts to develop a network of truck stop owners.
Low number of potential participants	Volume of traffic through the truck stop was lower than expected	Investigate user patterns at the truck stop so study staff are present at the right times.
Enrolling drivers	It can be difficult to engage drivers.	Train study staff on engagement strategies and consider this in survey re-design.
Survey design	Completing the survey took more time than anticipated and should be shortened.	Shorten/re-design survey prior to future study.
Survey implementation	Internet connection was unstable so tablet could not be consistently used.	Ensure back-up means for survey implementation.

The data collection team noted that many respondents agreed to the study as a social activity. Considering the recent literature on driver's work stress and poorer mental health the investigators consider mental health an important area to explore in future work (Apostolopoulos et al., 2016; Garbarino et al., 2018; Hege et al., 2019).

### Discussion

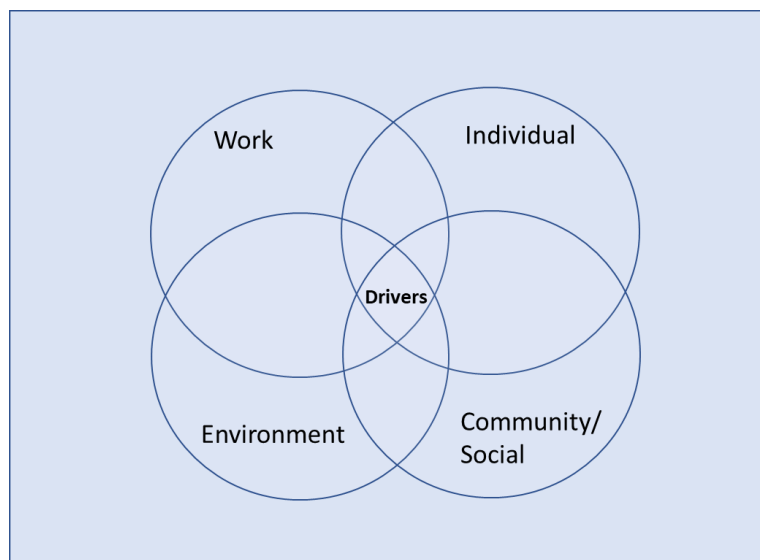
While only a small pilot study of 18 participants, the data gathered is consistent with other findings on long-haul drivers; the health issues and concerns reported align well with existing literature as summarized in the Introduction. The pilot study findings help to illustrate the cumulative

risk assessment concept of stressor exposures across multiple, overlapping health domains:

- Work: stress and other exposures (time pressure, diesel emissions)
- Individual: person-level health and risk factors (older age, musculoskeletal problems)
- Environment: Physical environmental needs (fitness facilities, healthy food)
- Community and social: Desire for social interaction

Figure 2 illustrates this framework. Long-haul drivers are at the center, experiencing the potentially health damaging and/or health promoting aspects of each domain.

Figure 2. Drivers in a cumulative risk framework [adapted from (Fox et al., 2018)]



Human health risk assessment (HHRA) is an integral part of environmental and occupational health decision making. The HHRA process is designed to organize and translate research on hazards (biological, chemical, physical, psychosocial, etc.), their health effects, and population exposures and susceptibilities to characterize or estimate health risks to inform risk management (Abt et al., 2010; National Research Council Committee on Improving Risk Analysis Approaches Used by the U.S. EPA, 2009). The cumulative risk literature for the occupational health field has grown over the past decade featuring conceptual models, examples and applications to support its practice (Fox et al., 2018; Lentz et al., 2015; Maier et al., 2017; Niemeier et al., 2020; Schulte et al., 2012; Williams et al., 2012). These models and concepts may help operationalize the syndemic idea in the design and translation to risk management of long-haul driver (and other worker) health studies, as described below.

Achieving worker health protection from harmful conditions means translating research into risk management actions. As recommended by the National Research Council, research findings may be translated more directly into health-protective actions if studies are designed with the risk management context in mind (National Research Council Committee on Improving Risk Analysis Approaches Used by the U.S. EPA, 2009). The risk management context includes both the risk manager or decision maker and relevant stakeholders. Thinking about long-haul drivers both the employer and the driver are risk managers/decision makers and there are many potential stakeholders that could influence driver health including co-workers, drivers' family and friends, equipment makers, and truck stop owners, among others. Table 4 provides examples of these risk managers and stakeholders organized by the domains of the cumulative risk framework.

Table 4. Drivers' concerns, risk managers and stakeholders in a cumulative risk framework

Affected and Interested Parties	Work Domain	Social/Community Domain	Individual Domain	Environmental Domain
Drivers	Time pressure and work strain Sedentary work Diesel emissions High rates of injury Whole body vibration	Inadequate work-life balance Isolated from home and local services	Predominantly male Older age Perceived stress Pre-existing health conditions	Variable Preferred activities may not be available
Risk managers or decision makers	Drivers Employers Regulators Truck and equipment manufacturers	Drivers Family and friends	Drivers	Drivers Government agencies (local and national) Truck stops Businesses
Stakeholders	Co-workers	General public	Employers	General public

	Businesses General Public	Truck stops Local businesses	Regulators Family, friends Co-workers General public	
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The driver is a critical decision maker for their own health across all domains but may not have complete discretion in all circumstances and must comply with employer and regulatory mandates such as the Federal Motor Carrier Safety Administration hours of service rule developed to reduce driver fatigue and related crash risk (Federal Motor Carrier Safety Administration, 2011). Further, as the occupational health Hierarchy of Controls suggests, the most effective controls or interventions are typically beyond the control of the worker alone and fall within the purview of managers or employers (e.g., eliminate the hazard, find a substitute for the hazard, change work procedures or other administrative action) (National Institute for Occupational Safety & Health, 2015).

While truck drivers are responsible for their own health, preventive health management and opportunities can be systemically improved for these itinerant workers. Truck driver wellness programs have developed over time with models that work through trucking companies as well as with individual owner-operators; these programs are part of the larger workplace wellness field (Healthy Trucking of America, 2021; Rolling Strong, 2019). As suggested by the cumulative risk assessment framework and the various decision-makers and stakeholders in matters of driver health, other opportunities to support driver health could include other types of partnerships, for example, companies working with the truck stop owners to improve healthy food options at truck stops. In addition, while some truck stops are located in isolated areas, most are in or on the outskirts of other permanent communities. Communications by employers and truck stop owners about the health, fitness, and outdoor amenities in the adjacent community could facilitate use by drivers, e.g., providing maps of parks, trails, recreation and fitness facilities and social events, programs, farmers markets, libraries and drop-in classes happening nearby. A goal could be to increase education around the need for health prevention, provide awareness of positive, life-enhancing opportunities, and make the right choice the easy choice, even for truck drivers on the move.

### Conclusions

A scoping review looking at interactions among co-exposures (one way to operationalize cumulative risk in data analysis) covering worker literature from the 1980s through 2017 did not find any studies of drivers (Fox et al., 2021). Assessing cumulative risks of drivers is an important area for additional research. Considering the cumulative risk framework and pilot study results and lessons learned, a shortened and redesigned survey should

include questions on work stress, time stress, mental health and social needs.

Human health research applied in risk assessment is a foundation of occupational health risk management. Considering cumulative risk assessment concepts in occupational health research design can facilitate holistic research considering syndemics, other co-exposures, risk factors and mitigators across multiple domains of health to expand potential risk management options for improved worker health protection.

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## References

- Abt, E., Rodricks, J. V., Levy, J. I., Zeise, L., & Burke, T. A. (2010). Science and decisions: advancing risk assessment. *Risk analysis : an official publication of the Society for Risk Analysis*, 30(7), 1028-1036. doi:10.1111/j.1539-6924.2010.01426.x
- Apostolopoulos, Y., Sönmez, S., Hege, A., & Lemke, M. (2016). Work Strain, Social Isolation and Mental Health of Long-Haul Truckers. *Occupational Therapy in Mental Health*, 32(1), 50-69. doi:10.1080/0164212X.2015.1093995
- Combs, B., Heaton, K., Raju, D., Vance, D. E., & Sieber, W. K. (2018). A Descriptive Study of Musculoskeletal Injuries in Long-Haul Truck Drivers: A NIOSH National Survey. *Workplace health & safety*, 66(10), 475-481. doi:10.1177/2165079917750935
- Cybersecurity & Infrastructure Security, A. (2020). [Guidance on the essential critical infrastructure workforce]. Available at: <https://www.cisa.gov/publication/guidance-essential-critical-infrastructure-workforce>
- EPA. (2003). Framework for Cumulative Risk Assessment. Retrieved from [https://www.epa.gov/sites/production/files/2014-11/documents/frmwrk\\_cum\\_risk\\_assmnt.pdf](https://www.epa.gov/sites/production/files/2014-11/documents/frmwrk_cum_risk_assmnt.pdf)
- Farzaneh, R., Penbrooke, T., & Zietsman, J. (2018) Workshop 3. Freight, Air Quality, Occupational Health: Truck Driver Wellness Pilot Study. Available at: <https://events.tti.tamu.edu/conference/2019-cartech-symposium/program/>.
- Federal Motor Carrier Safety, A. (2011). Hours of Service of Drivers. *Federal Register*, 76(248), 81134-81188. Available at: <https://www.govinfo.gov/content/pkg/FR-2011-12-27/pdf/2011-32696.pdf>
- Fox, M. A., Niemeier, R. T., Hudson, N., Siegel, M. R., & Dotson, G. S. (2021). Cumulative Risks from Stressor Exposures and Personal Risk Factors in the Workplace: Examples from a Scoping Review. *International journal of environmental research and public health*, 18(11), 10.3390/ijerph18115850. doi:5850
- Fox, M. A., Spicer, K., Chosewood, L. C., Susi, P., Johns, D. O., & Dotson, G. S. (2018). Implications of applying cumulative risk assessment to the workplace. *Environment international*, 115, 230-238. doi:S0160-4120(17)31986-4
- Garbarino, S., Guglielmi, O., Sannita, W. G., Magnavita, N., & Lanteri, P. (2018). Sleep and Mental Health in Truck Drivers: Descriptive Review of the Current Evidence and Proposal of Strategies for Primary Prevention. *International journal of environmental research and public health*, 15(9), 10.3390/ijerph15091852. doi:E1852
- Healthy Trucking of America. (2021). Healthy Trucking of America: Healthy Solutions to Keep America Moving. <https://www.healthytruck.org/>
- Hege, A., Lemke, M. K., Apostolopoulos, Y., & Sönmez, S. (2018). Occupational health disparities among U.S. long-haul truck drivers: the influence of work organization and sleep on cardiovascular and metabolic disease risk. *PLOS One*, 13(11), e0207322. doi:10.1371/journal.pone.0207322

- Hege, A., Lemke, M. K., Apostolopoulos, Y., Whitaker, B., & Sönmez, S. (2019). Work-Life Conflict among U.S. Long-Haul Truck Drivers: Influences of Work Organization, Perceived Job Stress, Sleep, and Organizational Support. *International journal of environmental research and public health*, 16(6), 984. doi:910.3390/ijerph16060984. doi:10.3390/ijerph16060984
- Horton, R. (2020). Offline: COVID-19 is not a pandemic. *The Lancet*, 396(10255), 874. [https://doi.org/10.1016/S0140-6736\(20\)32000-6](https://doi.org/10.1016/S0140-6736(20)32000-6)
- International Physical Activity Questionnaire (IPAQ). (2022). Downloadable questionnaires. Available at: [https://sites.google.com/site/theipaq/questionnaire\\_links](https://sites.google.com/site/theipaq/questionnaire_links)
- Lemke, M. K., Apostolopoulos, Y., Hege, A., Wideman, L., & Sönmez, S. (2017). Work organization, sleep and metabolic syndrome among long-haul truck drivers. *Occupational medicine (Oxford, England)*, 67(4), 274-281. doi:10.1093/occmed/kqx029
- Lemke, M. K., Apostolopoulos, Y., & Sönmez, S. (2020). Syndemic frameworks to understand the effects of COVID-19 on commercial driver stress, health, and safety. *Journal of transport & health*, 18, 100877. doi:10.1016/j.jth.2020.10087
- Lentz, T. J., Dotson, G. S., Williams, P. R., Maier, A., Gadagbui, B., Pandalai, S. P., . . . Mumtaz, M. (2015). Aggregate Exposure and Cumulative Risk Assessment--Integrating Occupational and Non-occupational Risk Factors. *Journal of occupational and environmental hygiene*, 12 Suppl 1, 112. doi:10.1080/15459624.2015.1060326
- Maier, A., Williams, P. R. D., & Dotson, G. S. (2017). Risks in Combination: Addressing cumulative risk in the occupational environment. *The Synergist*, May 2017. Available at: <https://synergist.aiha.org/201705-risks-in-combination>
- National Institute for Occupational Safety & Health (2015). Hierarchy of Controls. Available at: <https://www.cdc.gov/niosh/topics/hierarchy/default.html>
- National Research Council Committee on Improving Risk Analysis Approaches Used by the U.S. EPA. (2009). *Science and Decisions: Advancing Risk Assessment*. doi:NBK214630
- Newnam, S., Koppel, S., Molnar, L. J., Zakrajsek, J. S., Eby, D. W., & Blower, D. (2020). Older truck drivers: How can we keep them in the workforce for as long as safely possible? *Safety Science*, 121, 589-593. <https://doi.org/10.1016/j.ssci.2019.02.024>
- Niemeier, R. T., Williams, P. R. D., Rossner, A., Clougherty, J. E., & Rice, G. E. (2020). A Cumulative Risk Perspective for Occupational Health and Safety (OHS) Professionals. *International journal of environmental research and public health*, 17(17), 6342. doi: 6310.3390/ijerph17176342.
- Penbrooke, T.L. (2010). *US Antarctica Recreation Program Review, Needs Assessment, and Plan*. Contracted by Raytheon Polar Services for the National Science Foundation. GreenPlay, LLC. Broomfield, CO.
- Rolling Strong. (2019). Rolling Strong: Corporate Wellness. Available at: <https://rollingstrong.com/corporate-wellness/>



- Schulte, P. A., Pandalai, S., Wulsin, V., & Chun, H. (2012). Interaction of occupational and personal risk factors in workforce health and safety. *American Journal of Public Health*, 102(3), 434-448. doi:10.2105/AJPH.2011.300249
- Thiese, M. S., Moffitt, G., Hanowski, R. J., Kales, S. N., Porter, R. J., & Hegmann, K. T. (2015). Repeated Cross-Sectional Assessment of Commercial Truck Driver Health. *Journal of occupational and environmental medicine*, 57(9), 1022-1027. doi:10.1097/JOM.0000000000000522
- U.S. Department of Health and Human Services. (2018). *Physical Activity Guidelines for Americans*, 2nd edition. Washington, DC: U.S. Department of Health and Human Services. Available at: <https://health.gov/our-work/nutrition-physical-activity/physical-activity-guidelines/current-guidelines>
- Williams, P. R., Dotson, G. S., & Maier, A. (2012). Cumulative Risk Assessment (CRA): transforming the way we assess health risks. *Environmental science & technology*, 46(20), 10868-10874. doi:10.1021/es3025353