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COMMENTARY

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A blueprint for a new commercial driving epidemiology: An emerging paradigm grounded in integrative exposome and network epistemologies

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Abstract

Excess health and safety risks of commercial drivers are largely determined by, embedded in, or operate as complex, dynamic, and randomly determined systems with interacting parts. Yet, prevailing epidemiology is entrenched in narrow, deterministic, and static exposure-response frameworks along with ensuing inadequate data and limiting methods, thereby perpetuating an incomplete understanding of commercial drivers' health and safety risks. This paper is grounded in our ongoing research that conceptualizes health and safety challenges of working people as multilayered "wholes" of interacting work and nonwork factors, exemplified by complex-systems epistemologies. Building upon and expanding these assumptions, herein we: (a) discuss how insights from integrative exposome and network-science-based frameworks can enhance our understanding of commercial drivers' chronic disease and injury burden; (b) introduce the "working life exposome of commercial driving" (WLE-CD)—an array of multifactorial and interdependent work and nonwork exposures and associated biological responses that concurrently or sequentially impact commercial drivers' health and safety during and beyond their work tenure; (c) conceptualize commercial drivers' health and safety risks as multilayered networks centered on the WLE-CD and network relational patterns and topological properties—that is, arrangement, connections, and relationships among network components—that largely govern risk dynamics; and (d) elucidate how integrative exposome and network-science-based innovations can contribute to a more comprehensive understanding of commercial drivers' chronic disease and injury risk dynamics. Development, validation, and proliferation of this emerging discourse can move commercial driving epidemiology to the frontier of science with implications for policy, action, other working populations, and population health at large.

KEYWORDS

commercial driving epidemiology, complex networks, truck drivers, working life exposome

1 | INTRODUCTION

Regional and long-haul drivers of large trucks (hereafter commercial drivers) experience a disproportionate chronic disease and injury burden.[1,2] This burden is markedly characterized by a multitude of complex, multilayered, interacting, and evolving factors and nested systems.[3] Yet, prevailing epidemiological research remains grounded in traditional exposure-response epistemologies and methodologies.[3,4] The enduring convergence of these factors confines the comprehensive examination of commercial drivers' chronic disease and injury burden, thus maintaining a suboptimal understanding of its underlying etiology.

To overcome these stalemates at the nexus of occupational, chronic disease, and injury epidemiology, epistemologies conducive to studying the totality and complexity of working people's lifelong health and safety challenges, by examining them as "wholes" with interacting parts,[5] are quite overdue. Hence, in this paper, we: (a) discuss how epistemologies grounded in integrative exposome and network sciences can enhance understanding of commercial drivers' chronic disease and injury burden by introducing the "working life exposome of commercial driving;" (b) conceptualize commercial drivers' health and safety risks as complex networks and initiate the unpacking of this multilayered structure; and (c) elucidate how integrative exposome- and network-science-based epistemologies and methodologies can contribute to a better understanding of commercial drivers' chronic disease and injury dynamics.

Throughout this paper, we extensively use transportation-specific and technical concepts and acronyms that are relatively new for both general and commercial driver health and safety research audiences. Hence, Table 1 provides an abbreviated lexicon.

2 | COMMERCIAL DRIVING EPIDEMIOLOGY: REVIEWING THE EVIDENCE

About 3.5 million commercial drivers[6] work and live away from home for extended periods, spending most of their time in truck cabins, loading and unloading terminals, warehouses, truckstops, roadways, and rest areas.[7] Their broad work environment and to an extent, their lives and overall wellbeing are largely defined by government transportation and labor policies (e.g., hours-of-service [HOS] rules, medical certification) and corporate policies, regulations and operations (e.g., by-the-mile pay systems).[7,8] In these milieux, commercial drivers experience excess work-related strains with far-reaching, oftentimes intractable, health and safety repercussions. Thus, unsurprisingly commercial drivers are placed among the unhealthiest occupational cohorts.[9]

Largely due to the impact of large truck collisions and resulting traffic interruptions, injuries and fatalities, government and corporate priorities along with empirical research have heavily focused on roadway safety.[10,11] Epidemiological investigations have largely attributed these safety incidents to drivercentric, proximal determinants (e.g., distracted driving, traffic violations),[12,13] mostly overlooking the underlying organizational and structural determinants. Few exceptions include studies delving into, for example, the role of compensation methods in safety outcomes.[14] Yet, despite consistent alarming statistics, the health of commercial drivers and contributing underlying etiology have taken a back seat in epidemiological research.

In a labor-intensive, time-constrained work environment, commercial drivers experience a plethora of interrelated strains, including excess levels of: (a) psychological pressures such as stress, isolation, and related burdens[15] amidst long and irregular workshifts (up to 14 consecutive hours a day and 70 hours in an 8-day span, when adhering to HOS rules)[16] and associated fatigue and sleep deprivation[17,18]; (b) adverse physical, environmental, chemical, and noise exposures[19,20]; (c) behavioral concerns such as sedentariness, limited physical activity, and ergonomic problems[21,22]; and (d) work-life balance and home and family pressures.[23] Additionally, while on the road, commercial drivers are faced with limited affordable healthful food choices as well as access to quality and affordable healthcare services.[24,25]

In these health and safety risk-laden milieux, commercial drivers experience chronic and typically interrelated, excess comorbidities. Key among them are excess anxiety or depression, chronic and acute stress, obesity, cardiometabolic diseases, cancer, sleep problems and disorders, musculoskeletal risks, injuries, and fatalities.[26-29] These quite common disease and injury outcomes are deemed rather disproportionate, especially when compared to both other occupational cohorts and the general population.[30] These patterns also corroborate the presence of syndemics[31,32]—that is, aggregation of two or more concurrent or sequentially interlinked disease and injury clusters exacerbated by underlying sociostructural and professional conditions.

Unsurprisingly, originating primarily from trucking companies and the federal government, mainly roadway safety-centered prevention efforts are heavily drivercentric.[33] They typically focus on modifying driving behavior by addressing safety training, compliance with safety regulations, safety-related technology (e.g., electronic logging devices), and incentives for safety performance.[34,35] Yet, more recently, there has been an emphasis on improving vehicle and roadway environment safety as well.[36] Along these lines, relatively few trucking fleets are also implementing health and wellness programs aimed at improving safety either directly (e.g., screening for and treating sleep disorders) or indirectly (e.g., managing obesity).[37] These efforts have been largely shaped by federal actions, such as Department of Transportation (DOT) medical examination requirements or mandated electronic logging devices, among others. While these actions have been positive for some (undisclosed) individual drivers, they have produced overall inconsequential population-level results, thereby leading to the continuation and in some cases, even exacerbation of drivers' disease and injury burden disparities.[38]

3 | IMPASSES OF EPIDEMIOLOGICAL RESEARCH

Prevailing commercial driving epidemiology has been marked by a stark underestimation of the scale, diversity, interdependability, spatiotemporality, and complexity of a plethora of multifactorial

TABLE 1 Glossary (adapted to population health and commercial drivers).

CANoNs	Complex adaptive networks of networks.
Complex networks	Graphs with nontrivial topological properties (e.g., high clustering coefficient) that do not occur in simple networks (e.g., random graphs) but in networks representing real systems (e.g., social networks).
CVD	Cardiovascular disease.
DOT	U.S. Department of Transportation.
Edges (network)	Connections between network nodes indicating relationships (e.g., physical interactions) among connected nodes.
EPHOR	European Union-based Exposome Project for Health and Occupational Research.
Exposome	Cumulative influences and associated biological responses throughout lifespan.
Exposome science	Study of all lifetime influences on health and safety grounded in novel scientific and technological innovations.
Ex-WAS	Exposome-wide association studies.
FHWA	U.S. Federal Highway Administration.
FMCSA	U.S. Federal Motor Carrier Safety Administration.
Genome	Complete set of genes.
Graph theory	Branch of mathematics studying graphs and their properties; graphs are mathematical structures made up of nodes connected by edges—used to model pairwise relations between entities.
HOS	U.S. Department of Transportation Hours-of-Service rules for professional drivers.
Lifecourse theory	Study of interacting biological, behavioral, psychological, social and environmental factors shaping health across people's lives.
Networks	Group of entities (nodes) connected by lines (edges)—oftentimes represented by graphs.
Network science	Study of complex social, health, and other networks, drawing on graph theory (mathematics), statistical mechanics (physics), data mining/information visualization (computer science), inferential modeling (statistics), and social structure (sociology).
Network topology	Arrangement and connections of network entities.
Nodes (network)	Basic unit of graphs; depending on application, a node can represent diverse factors capable of creating, receiving, processing, sending, or redistributing data over a network.
OSHA	U.S. Occupational Safety and Health Administration.
Phenome	Set of all observable traits or characteristics of organisms.
Syndemics	Aggregation of two or more concurrent or sequential interlinked disease or injury clusters exacerbated by underlying sociostructural and professional conditions.
WLE	Working life exposome.
WLE-CD	Working life exposome of commercial driving.
WLE-CD-WAS	Working life exposome of commercial driving-wide association studies.

work and relevant nonwork factors affecting drivers' overall health, safety, and wellbeing over their working lifespan and beyond. This enduring underestimation has literally shaped the epidemiological research process along lines of theory, methodology, and analysis.

Theoretical foundations are overall grounded in narrowly defined exposures unfolding primarily in a few components of commercial drivers' work milieux (e.g., truck cabins), and mainly atheoretical, linear, drivercentric, reductionist, deterministic, and static conceptualizations.[39] Linear causal thinking and single-level causal explanations, in particular, are heavily used by prevailing conceptualizations. As for the former, a profusion of reciprocal and continual connections and movements among factors and systems over time are largely absent, while for the latter, there is an overreliance on intrapersonal factors at the expense of crucial institutional, structural, organizational, and other meso-/macro-level factors. Such narrow conceptualizations have typically led to the collection of inadequate data that often omit critical social, economic, political, and other macro/meso domains.

These narrow conceptualizations have clearly impaired methodological frameworks: (a) research designs are mainly cross-sectional, drivercentric, and small scale;[40] (b) while there exist longitudinal data studies of overall average quality and adequacy,[41] commercial driving epidemiology is defined by the absence of invaluable, high-quality prospective studies; and (c) data collection methods are almost solely based on epidemiological surveys, thus limiting types of data that mainly include common or high-risk workplace exposures (e.g., irregular driving shifts), and common or hard health and safety outcomes (e.g., obstructive sleep apnea). A few exceptions come from roadway safety research where advanced technologies (e.g., onboard monitoring systems, actigraphy, smartphone apps) are being used.[42,43] Of course, logistical challenges (e.g., driver mobility and turnover) and corporate barriers (e.g., frequent unwillingness of fleets and drivers to facilitate comprehensive primary data collection) must be duly noted. Collectively, these factors have adversely affected quality and adequacy of collected data.

Largely grounded in a priori hypotheses, analytical frameworks mainly delve into potential associations between predetermined single, common workplace driver-centered exposures—treating others as confounders or effect modifiers—and single or classes of related, common driver health and safety outcomes at a time (e.g., relationship between fatigue, sleep disorders, and close calls for crashes).[44,45] When rarely, mixtures of different exposures (e.g., organizational characteristics of work, dietary patterns, syndemic outcomes) are examined, neither their compositional complexity is fully disentangled, nor methodological innovations reflecting multiple exposures and components are employed. Moreover, this overall inadequacy has also affected the analysis of existing (inadequate) data.

The confluence of the foregoing epistemological assumptions and field realities has hampered the implementation of comprehensive, rigorous, especially longitudinal, large-scale epidemiological research.[46] Subsequently, we still have limited knowledge of: (a) the extent and complexity of multilayered exposures and their influences on driver health and safety; (b) how interactions among structural (e.g., corporate operations) with meso-/micro-level (e.g., driver sleep and dietary patterns) exposures influence diverse health and safety outcomes; (c) the spatiotemporal variability of exposures and their influences on driver health and safety; (d) what and how biological pathways and mechanisms connect synergistic exposures and outcomes; (e) how an aging workforce can handle increasing professional pressures and effects on driver health and safety; and (f) how a complete account of drivers' work and relevant nonwork exposures and their interactions affect their health and safety over time.

4 | COMMERCIAL DRIVERS' RISKS AS INCLUSIVE "WHOLES"

The foregoing description and analysis point toward the need for more realistic conceptualizations of commercial drivers' health and safety risks and their consequences. To that end, the following sections delve into how comprehensive novel approaches can enhance commercial driving epidemiology.

4.1 | Moving from drivercentric to holistic frameworks

Grounded in complex systems frameworks, the 1990s brought about an epistemological transition in population health sciences by highlighting the significance of the overlooked "whole" in explaining health and safety challenges.[5] Accumulated evidence suggests that these challenges can be more fully understood when examining them as "wholes" with interacting parts—that is, with the comprehensive inclusion of all possible contributing domains.[5] Overall, drawing upon macrosocial syndemic,[31] lifecourse,[47] and ecosocial[48] theoretical frameworks, and grounded in exposome[49] and network[50] sciences, these epistemologies highlight the health implications of lifetime nongenetic influences (with the genome explaining a small proportion of the phenome[51]) and that connections (edges in network language) among factors (nodes in network language) define the function of "wholes" (networks/systems, represented as graphs[50]), respectively. Synergies of exposome and network sciences provide a logical avenue for the examination of intractable health and safety challenges of working (and nonworking) people.

Yet, occupational and commercial driving epidemiology alike have barely incorporated these combined innovations; and the few, limited exceptions do not go far enough.[52–55] Two research groups are presently grappling with these ideas in the context of work, health, and safety. First, empirical efforts of European Union scientists have advanced the groundbreaking Exposome Project for Health and Occupational Research (EPHOR),[56] and are currently collecting lifetime, diverse occupational and related nonoccupational data to delineate working people's health. Second, going a few steps further, evolving programmatic and empirical efforts of scientists from the U.S. are exploring how integrative exposome and network science-based frameworks can unravel lifetime health and safety risks of working people. Along these lines, this group (including this paper's authors) has provided a more thorough account of the working life exposome, while stressing its potential contribution to understanding the "indispensable whole of work and population health and safety."[5] These trailblazer frameworks can guide the overdue transition from narrow, static, and isolated workplace drivercentric exposures to holistic (work and relevant nonwork), lifetime, interacting exposures that would only enhance occupational and commercial driving epidemiology.

4.2 | Introducing the "working life exposome of commercial driving"

Expanding our ongoing work[5] in the context of relevant research from chronic disease, injury, and occupational epidemiology; exposome; and commercial driver health and safety (scan of PubMed 2000–2023), including seminal relevant publications of the National Academies,[57-62] we introduce the emerging "working life exposome of commercial driving" (WLE-CD). We define the WLE-CD as the totality of an array of heterogeneous, multifactorial and multilayered, and interdependent work, work-related, and in/directly relevant nonwork exposures and associated biological responses and endogenous processes that concurrently or sequentially impact commercial drivers' wellbeing from conception onwards, throughout and beyond their working lifetime. This working definition assumes that the commercial driving occupation lasts for several years, and while comprehensive data on the average commercial driver's tenure remain elusive, the review of various reliable sources indicates that most drivers drive professionally more than 10–15 years.[63-67]

Below we provide a comprehensive description of multilayered WLE-CD components: the first four components depict the external, while the fifth depicts the internal exposome (as per exposomic conventions).[68] This description highlights how interdependencies between social structure and individual agency shape health and safety over the lifecourse.[69]

Commercial driving exposures unfold in work milieux and have immediate or delayed effects on drivers' wellbeing beyond their work tenure. They fall under:[70-73] (a) design, content, and conditions of commercial driving including workload characteristics (e.g., hours/schedules/irregularity, cargo types/routes, work assignment dispatching); organizational work environment and associated driver psychological demands (e.g., low job control, inadequate rewards, relationships with other drivers and dispatchers); workplace exposures, including roadway conditions, roadway users, vehicle condition, physical, ergonomic, and chemical strains for drivers, conditions in and around workplaces, and driver remuneration; (b) driver health-/safety-related behaviors on the road including fatigue, breaks/rest/sleep, fatigue management; healthful food consumption; physical activity; and substance use; and (c) driver work-life balance away from home including time distribution across road and home, loneliness, stress, family/friends/significant others/partners, other pressures, and mental health and wellbeing.

Commercial driving-defining exposures originate outside the immediate work milieux as mainly transportation and labor policies and regulations, but define "commercial driving exposures," while affecting drivers' lives and have a sustained bearing on driver wellbeing during and well beyond work tenue. They mainly include:[74-76] (a) government transportation policies such as Motor Carrier Act, Federal Motor Carrier Safety Administration's HOS regulations and their enforcement, and Federal Highway Administration's funding policies; (b) government labor policies such as motor-carrier exemption under the Fair Labor Standards Act and minimum wage enforcement; (c) corporate policies, regulations, and operations including driver recruitment and training practices and procedures, scheduling and dispatching, use of in-truck technologies, health and wellness programs, job security, compensation methods, and benefits and rights; (d) labor market characteristics such as occupational segregation, labor market conditions, driver shortages and turnover, an aging workforce, and supply chain problems; and (e) labor unions (e.g., union access to driver workplaces, unionization protections, collective bargaining).

Commercial drivers' broad nonwork exposures involve institutional, political, socioeconomic, demographic, educational, labor, food, health, housing, land use, transport, and environmental forces, regulations, policies, practices, as well as their implementation, that shape the wellbeing of working and nonworking people alike. Representative government-based examples include:[77-80] (a) social and health policies (e.g., universal, quality and affordable healthcare access, subsidized housing for low-income persons, retirement and pension programs); (b) labor policies (e.g., unemployment benefits and insurance, Occupational and Safety and Health Administration regulations, protections and enforcement, workers' compensation programs); (c) environmental policies addressing water and air quality and pollution, among other related matters; (d) agricultural and food policies (e.g., food production, processing, distribution of safe, affordable, and healthy food); and (e) economic and financial, educational, and health resources.

Commercial drivers' work-dependent, nonwork exposures originate outside broad work milieux but are heavily affected by work and interact with and are affected by foregoing exposures, which synergistically shape drivers' overall wellbeing throughout their lives. They mainly include commercial drivers':[81-84] (a) personal and family social and economic resources (e.g., household income, educational opportunities, social capital, home ownership); (b) personal and family neighborhood, housing conditions and realities; (c) personal and family health history including family traumas (death, divorce, illness); (d) health-related behaviors outside work (e.g., diet, substance misuse, sedentariness); (e) work-life balance pressures at home (e.g., inflexible workhours, shiftwork, lack of paid sick and vacation leave, unemployment, excess home responsibilities); and (e) sociodemographic attributes and factors.

Finally, *commercial drivers' biological and other responses to all exposures* occur gradually as the cumulative embodiment of the foregoing four domains and influences. As endogenous processes and mechanisms, they include various physiological disruptions, such as responses to chronic and acute psychological distress, hormonal and metabolic challenges and imbalances, various forms of inflammation, chronobiological changes, oxidative challenges, fatigue, aging, sleepiness, epigenetics, and syndemic states with far-reaching ramifications for the health, safety, and wellbeing of commercial drivers.[85–89]

4.3 | Examining commercial drivers' risks as multilayered networks

The foregoing description of the WLE-CD reveals that the mechanisms and pathways of commercial drivers' chronic disease and injury challenges are markedly determined by, embedded in, or operate as complex adaptive networks of networks (CANoNs).[90-93] This representation is important especially because exposures induce health-related phenotype changes not as single but as a collection of interrelating agents acting in unison.[94] Hence, commercial drivers' health and safety challenges are attributable to diverse, multisource and multilevel factors (nodes in a network representation) that are interdependent and self-organized, generate feedbacks and emergent patterns, follow simple rules (e.g., based on theoretical propositions), and evolve over time. These "meganodes" include multifactorial, multilayered WLE-CD components and commercial drivers' genome and chronic disease and injury outcomes, with each node including several nested factors, layers, other networks, and larger systems. Simply put, interactions among all nongenetic risk factors (exposome) and the genetic endowment (genome) produce a state of health or disease (phenome).[95-98] These meganodes interact among themselves in various ways, while similar processes and connections exist within nodes themselves—especially within the WLE-CD. The arrangement and connections (edges) of nodes, their spatial patterns, and especially their emergent topological properties (or network topology[99,100]) are of foremost importance in unravelling relational patterns and causal structures of drivers' health and safety risks. Figure 1 represents a heuristic portrayal of commercial drivers' health and safety risks as CANoNs.

While delineating the architecture of ordinary graphs—exemplified by pairwise node interactions represented by edges—has generated valuable insights in understanding and preventing health and safety risks,[101–103] it also comes with inherent constraints.[104] Like other complex networks (e.g., neural or metabolic systems), the multifactorial and multilayered nodes of this CANoN (i.e., the complex network of commercial drivers' health and safety risks) are anticipated to interact in larger groups and such interactions cannot be decomposed as linear combinations of dyadic couplings.[105] The existence of many-node, higher-order interactions are more fully represented by hypergraphs and hyperedges—with hypergraphs allowing us to model groups instead of only binary relations.[105,106] Early hypergraph-based investigations indicate that higher-order interactions may bear significant influences on networks, oftentimes leading to dynamic processes and even abrupt transitions between states.[107]

As with ordinary graphs, hypergraphs carry topological properties[108,109] that can influence the dynamics of networks. Most commonly used topological properties include: (a) degree distribution of a network: number of edges connecting to a node that can influence other network properties because degree distribution provides a high-level description of the network topology, for example, a scale-free network (where most nodes are connected to a low number of neighbors and there is a small number of high-degree nodes (hubs) providing high connectivity to the network); (b) shortest paths: shortest distance between any two nodes used to model flow of information and transmission; (c) transitivity (or modularity): presence of tightly interconnected nodes that are more internally connected than they are with the rest of the network (clusters/modules/communities); and (d) different types of centralities: denoting how important a node or an edge is for a given network property, such as the network's connectivity, proximity to other nodes, information or transmission flow, and others. Overall, these topological properties can have an influential bearing on other processes.[109] Both network relational patterns and topology are crucial for understanding complex health situations[110] because, together they can define quantitative patterns and measures of nodes and edges, thus, network localization and organization are reflected in topological parameters.

It is because of these features that we cannot effectively examine CANoNs by an a priori determination of a set of nodes and properties that are studied separately (e.g., associations between irregular workhours and commercial drivers' obesity) and then recombining these (and other) partial associations to understand

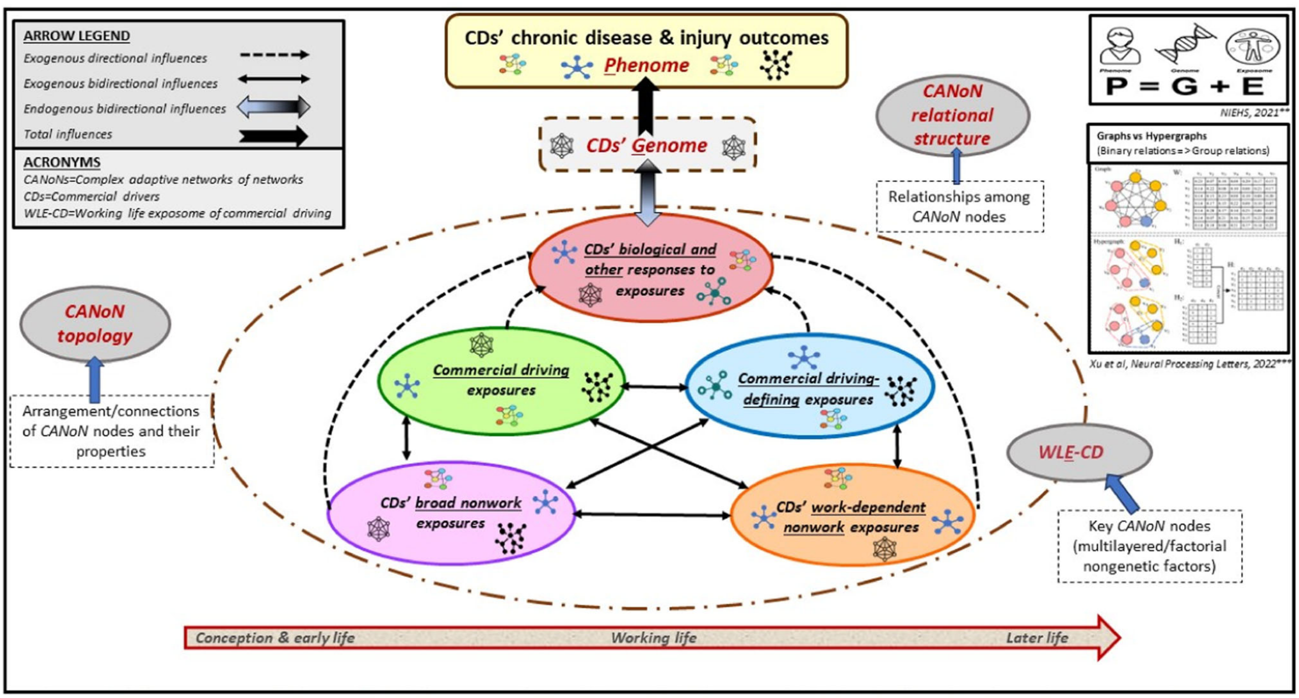

FIGURE 1 Simplified depiction of commercial drivers' health and safety risks as complex adaptive networks of network (CANoNs; hypergraphs) centered on working life exposome of commercial driving (WLE-CD) and CANoN attributes *Adapted from: https://pubmed.ncbi.nlm.nih.gov/37952240/, https://factor.niehs.nih.gov/2021/1/science-highlights/data-science, https://link.springer.com/article/10.1007/s11063-021-10684-7.

TABLE 2 The WLE-CD[1] influences commercial driver wellbeing throughout the lifecourse.[2]

Lifecourse (years)		0 10	20 30 40 50 60 70	80 90+
		Early life[3]	*Working life*	*Later life*
W L E - C D	CD exposures			
	CD-defining exposures			
	CDs'[4] broad nonwork exposures			
	CDs' work-dependent, nonwork exposures			
	CDs' biological/other responses to exposures			

[1]**WLE-CD**=Working life exposome of commercial driving;[2] It assumes that occupation lasts for several years (see p.5 of text);[3] **Early life** includes periconceptional and perinatal periods;[4] **CDs**=commercial drivers. **Solid** lines denote direct/actual influences and consequences; **Dotted** lines denote potential/residual/indirect influences and consequences.

the indispensable whole. It is necessary, therefore, to examine and model them as wholes (represented by CANoNs), with an emphasis on understanding interactions among various network entities, pathways, mechanisms, structures, and emergent influences over time. Table 2 depicts the lifecourse dimension of WLE-CD.

5 | PARADIGM SHIFT IN COMMERCIAL DRIVING EPIDEMIOLOGY

Foregoing evolving analysis accentuates the epistemological necessity for new directions in commercial driving epidemiology grounded in the strengths of exposome and network sciences. This emerging paradigm shift corresponds to actual health and safety challenges and emphasizes how integration of WLE-CD and CANoN theories and epistemologies can more efficiently explain commercial drivers' chronic disease and injury risks.

5.1 | Integrative exposome/network frameworks enabling the study of "wholes"

The integrative WLE-CD/CANoN conceptualization and associated innovations can catalyze significant enhancements in epidemiological research by extenuating the complexities of the indispensable whole of commercial drivers' chronic disease and injury risks. Below we outline potential contributions of emerging WLE-CD/CANoN-grounded frameworks, using "commercial drivers' cardiometabolic syndemics" that are among the foremost concerns of this occupational cohort[111]—as a case study.

5.1.1 | Theoretical enhancements

WLE-CD/CANoN-based frameworks enable understanding of commercial drivers' cardiometabolic syndemics as complex and dynamic, comprehensive wholes with interacting parts. Specifically, they can: (1) provide the theoretical basis to portray an array of multifactorial and interdependent work and related nonwork exposures that synergistically shape drivers' wellbeing; (2) recognize the totality, complexity, and concurrency of multiple, multilayered, multiscale, heterogeneous exposures; (3) highlight how interdependencies of exposures can influence drivers' health over their lifecourse; (4) extenuate the importance of structural transportation, labor, and other social factors and their interactions with biological mechanisms, thereby providing insights into informative biological pathways linking exposures to overall wellbeing; and (5) emphasize spatio-temporal dimensions of exposures, and especially how ramifications of working life exposures extend beyond drivers' tenure. These and related assumptions can also work as key propositions toward the development of a theory that frames commercial drivers' wellbeing. Last, these conceptual improvements will also define types of research questions asked, data collected, and hypotheses tested.

5.1.2 | Methodological enhancements

WLE-CD/CANoN-based frameworks can allow the: (1) systematic implementation of invaluable longitudinal designs underpinned by the ubiquitous complexity of commercial drivers' syndemics over their lifecourse; (2) examination of diverse driver cohorts, with an emphasis on more vulnerable groups (e.g., older or women drivers); (3) implementation of comprehensive designs that combine bottom-up and top-down approaches;[112] (4) employment of data collection methods beyond surveys, grounded in exposure biomarker technologies, geographical mapping and remote sensing technologies, smartphone applications, and personal exposure sensors, and high-throughput molecular "omics," among others; (5) collection of comprehensive (primary and secondary) data that cover common and less common multifactorial exposures, biological and related mechanisms, pathways, and markers, as well as diverse higher-/lower-prevalence outcomes; and (6) utilization of extant datasets[1,42,113,114] (based on large-scale data pooling from population, industry- or occupational cohorts) and various big data sources, including exploitation of both comprehensive and fragmented datasets, as well as collection of proxy measures to account for crucial pre-working life exposures. The systematic collection of comprehensive commercial driver health and safety data remains a necessity for novel epidemiological research.

5.1.3 | Analytical enhancements

Especially due to extensive knowledge gaps, WLE-CD/CANoN-based frameworks can facilitate both discovery- and hypothesis-driven analytical approaches: (1) inductive (untargeted) research—grounded in exposome-wide association studies/ExWAS[115-118] and network analysis,[119,120] among other relevant analytical innovations—can contribute to discovering causal signatures and fingerprints of exposures, thereby potentially uncovering new combinations of mechanisms generating or perpetuating syndemics, and (2) deductive research grounded in an array of traditional and novel correlation-/regression-based analytical methods can contribute to testing the plausibility of various evidence-supported hypotheses in delineating these syndemics. Along these lines, because traditional statistical approaches are not designed to delineate compound effects of WLE-CD/CANoN-based multifactorial and multilayered components, the employment of combinations of novel analytical methods—taking advantage of primarily stochastic analytical breakthroughs grounded in the use of mathematical, statistical, and computational innovations (e.g., machine learning, network analysis, simulation)[121-123]—can advance understanding of drivers' syndemics over their lifecourse. Also, methods employed in other health-focused exposome and network projects as well as science-originating network projects can be replicated or can catalyze the development of new methods appropriate for evolving commercial driver research needs. These frameworks can facilitate the identification of those exposures that trigger biological perturbations and changes leading to cardiometabolic syndemics, with an emphasis on sources, early markers, routes, combinations, and critical phases before, during, and beyond drivers' working lifetime.

5.1.4 | Beyond a "crude look at the whole"

When in 1990 renowned physicist Murray Gell-Mann emphasized the importance of "a crude look at the whole," he intended, among others, to underscore the imperative necessity of examining complex situations as wholes and then allowing possible simplifications to emerge from this approach.[124] Over three decades later, however, integrative WLE-CD/CANoN-based epistemologies and methodologies grounded in multifaceted ongoing scientific and technological breakthroughs allow us a more complete examination of the indispensable whole of health and safety challenges of working people.[5] Differently put, novel integrative WLE-CD/CANoN-based epistemologies and methodologies are promising a more comprehensive, useful look at the indispensable whole of commercial drivers' health and safety challenges.

5.2 | Other holistic approaches applicable to occupational health and safety

Other holistic epistemological and methodological approaches to population health, safety, and wellbeing, not specific to commercial driving but broadly applicable to population and occupational health and safety, have come to light over the past few decades. Some indicative examples can be found among various US and European exposome projects as well as the CDC/NIOSH Total Worker Health (TWH) program.

Since the emergence of the exposome by Christopher Wild in 2005,[125] as an important domain complementing the genome, there exist several European and US projects that have delved into the role of the totality of lifetime exposures in diverse health challenges. US-based examples include the CIRCLE (University of California, Berkeley), HERCULES (Emory and Georgia Tech Universities) and other diverse exposome research projects.[126,127] Indicative European examples include the EXPANSE and EPHOR (Netherlands), LONGITOOLS (Finland), EXIMIOUS (Belgium), HEAP (Sweden), and REMEDIA (France), which are diverse ongoing exposome projects.[128-133]

These and other similar and growing number of exposome projects can provide beneficial directions for enhancing and even transforming epidemiological research in the context of work, including commercial driving and transportation in general. Their focus on the totality of lifetime exposures and their interactions, as well as on the inclusion of synergistic scientific, methodological, analytical, and technological innovations can contribute to a more comprehensive understanding of complex and intractable population health and safety outcomes. Along these lines, there has also been growing discussion about the need for a grand Human Exposome Project to holistically and systematically explore the entirety of the exposure side of human health and disease.[134]

Since its inaugural presentation in 2011, CDC/NIOSH's TWH program[135] provides a definitely more integrated approach to occupational health, safety, and wellbeing. It is also worth mentioning here that, despite the crucial role of work in population health, the National Institutes of Health—among the two leading health agencies of the United States—announced its first funding opportunity call on "the role of work in health disparities" as late as 2021.[136] Among other reasons, this is critical because federal funding drives novel empirical research. Despite its significant strengths compared to more conventional approaches, the TWH program includes noteworthy limitations, especially when compared to the emerging paradigm shift in commercial driving epidemiology we are introducing herein. Specifically, while the TWH program integrates protection and promotion of the health and safety of working people along the lines of policies, programs, and practices, in its applied research component, it continues to maintain a narrow conceptual (mainly work-specific and time-specific focus), methodological (with overall inadequate data entrenched in the workplace that are largely behavioral), and analytical (largely deterministic and static exposure-response frameworks and limiting methods) lens.[137]

At the other end of the spectrum, the new paradigm we are introducing herein is grounded in the working life exposome—integration of lifelong work and related nonwork exposures and their interactions—and complex system/network sciences/frameworks, examination of intractable health challenges as wholes with interacting components, and commensurate novel methodological approaches and analytical techniques. Along these lines, accumulating empirical evidence indicates that time is ripe for a transformational epistemological transition in our field leading to a shift expanding from the current, relatively "narrow," occupational epidemiology to the more comprehensive and pragmatic "epidemiology of working life."

During these past two decades, exposomic and TWH approaches have made significant scientific and applied contributions to population and occupational health and safety research. Yet, because of various multifaceted challenges, these approaches have not been fully integrated into the prevailing paradigm in population health and safety.

5.3 | Leveraging network analysis within integrative exposome/network frameworks

In this section we present a small-scale proof-of-concept grounded in network analysis to demonstrate only a few, indicative portions of how the analytical strengths of the emerging paradigm can enhance our understanding of commercial drivers' health and safety challenges. Given that exposures induce health-related phenotype changes as combinations of interacting factors acting together[138] and that network relational and topological features provide invaluable insights on interrelations among exposures and outcomes,[139] network analysis is uniquely suited to describing, exploring, and understanding drivers' health and safety risks. It is our goal to substantiate how these holistic approaches can contribute to a better delineation of drivers' health and safety risks.

5.3.1 | Uncovering network relational patterns

Understanding how relationships between CANoN nodes may influence the behavior of the whole system (i.e., commercial drivers' health and safety risk vulnerability) is crucial. The main idea is that WLE-CD exposures and drivers' health and safety outcomes are interdependent, and we may miss crucial interplays unless we evaluate them as CANoNs. We can examine patterns of relationships between variables (e.g., relationships among CANoN nodes, contribution of groups of CANoN nodes to single and multiple outcomes), and how different WLE-CD exposures and outcomes may be related to each other, by either correlational or causal relationship that will lead to large-scale networks. Network analysis allows the exploration of a larger space of WLE-CD exposures and outcomes, where single connections will now be substituted by subsets of factors that are densely connected in the network representation, thereby providing deeper insights into complex risk etiology.

Figure 2 demonstrates a simplified network of commercial drivers' roadway safety, based on a small imperfect subsample ($N = 459$) of commercial drivers originating from our own work[140]—with roadway safety being a foremost concern for professional drivers.[10] While we anticipate the emergence of higher-order interactions and group relations among CANoN nodes (thus being open to highly novel network analyses), because of data limitations, we follow a more traditional network analysis path examining only binary relations between nodes—which nevertheless can reveal the strengths of the emerging paradigmatic direction.

A few explanatory variables (circles) represent factors related to commercial drivers' work (orange), cardiovascualr health (teal), sleep health (blue-gray), and lifestyle (purple). These variables are connected among themselves and to roadway safety outcomes (hexagons). Our main hypothesis is that commercial drivers' roadway safety outcomes are impacted by the entire system, as expressed by the combination and interdependence of factors leading to this network representation. For clarity, we include only four roadway safety outcome variables (lemon) corresponding to "no accidents," "more than 2 accidents," "no near misses," and "more than 5 near-misses." For each outcome, we compare the commercial driver subsample related to this outcome ("outcome sample") with the subsample of all other commercial drivers ("reference sample"). This comparison takes place for each explanatory variable separately and we determine whether the two variable distributions in these two subgroups can be considered statistically different from each other. If distributions are different, then we connect the variable to the outcome with a green line, when the variable value in the outcome sample is larger than in the reference sample, or with a red line, when the variable value is smaller in the outcome sample than in the reference sample. The distance between distributions is determined via a standard Kolmogorov-Smirnov test,[141] except for binary (yes/no) distributions which are tested using a χ^2 test.[142] Connections between explanatory variables are determined by linear correlations between pairs, using the whole driver sample. We use the Pearson coefficient[143] to quantify the connection strength between all explanatory variable pairs and impose a threshold, above which we assign a link connecting the given pair.

This representation shows that even with this small, imperfect sample of commercial drivers and a few explanatory variables, we get meaningful information out of this network. For example, the "more than 5 near-misses" outcome is directly linked to BMI, blood pressure, and age. This representation also shows that these network nodes do not act independently but, together with other nodes from the "cardiovascular health" cluster, form an intricate web of interdependencies, which need to be considered when planning possible interventions or other actions. Other interesting patterns, such as the lack of association between "work" and "more than 5

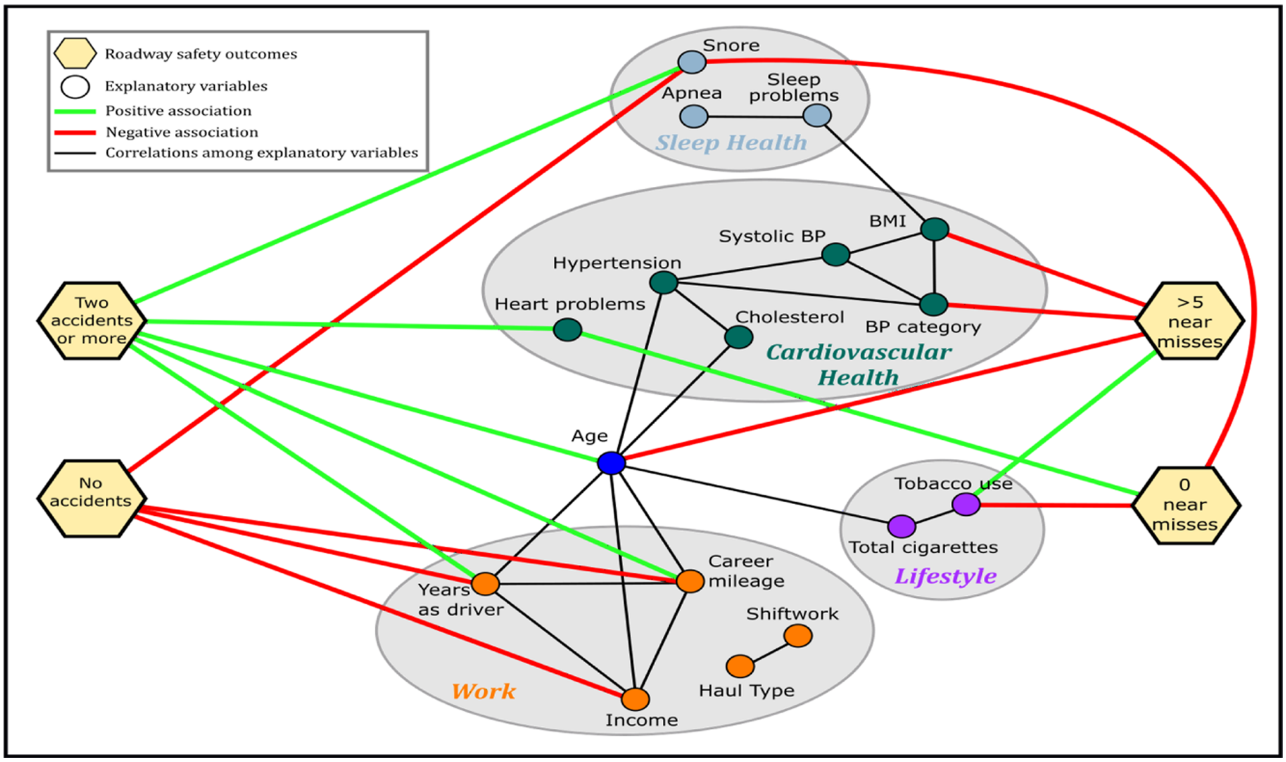

FIGURE 2 Network representation of commercial drivers' roadway safety.

near-misses" variables (given the association between "2 accidents or more" and "work" variables) and lack of direct association between "work" and "cardiovascular health" variables, require some explanation. While the former can be explained by the imperfect data used in this analysis (i.e., small subsample size, poor selection of limited cases out of a very large sample, few explanatory variables, quality of variable groupings) included in this proof-of-concept analysis, the latter corroborates the strengths of network analysis by indicating that associations between work and health are mediated by the age of drivers. We expect that a comprehensive, WLE-CD-informed data set and a subsequent network of larger scale will uncover factors or groups of factors that directly or indirectly have the highest impact on commercial drivers' roadway safety outcomes.

5.3.2 | Identifying network topological properties

Topological interdependencies (e.g., centrality, clustering)[144,145] among WLE-CD factors may influence commercial drivers' health and safety outcomes. For example, it would be useful to know which WLE-CD factors are more important or central than others in this CANoN and whether they are isolated or form strong clusters. Centrality measures, for example, can reveal groups of WLE-CD factors, whose CANoN location may affect many outcomes or connect otherwise disjointed CANoN areas. The identification of topological properties is not possible without a holistic network consideration.

Returning to our proof-of-concept example, "commercial drivers' roadway safety network" is a useful tool to examine complex interactions between multiple exposures because we can use network analysis to evaluate how different factors influence each other as isolated nodes or as a group, determine the importance of different explanatory variables in the global structure, estimate how different interventions may change the form of the network, etc. Centrality measures, for example, can reveal what categories of variables are dominant in the network as, for example, influencing or being influenced by most of the other exposures. In Figure 3, the "age" node (cobalt) has the highest degree centrality among explanatory variables—it is related to the largest number of exposures and outcomes and is the node that ties together different groups of factors. In addition, several centrality measures can be examined within variables as well (e.g., within age, as it may be that commercial drivers of varying age groups may have differing results related to roadway safety outcomes). Even though this is an anticipated result, it demonstrates how the network structure can provide an improved picture of interactions among multiple factors forming a global exposure system.

This network can be used to calculate roadway safety risk scores within subpopulations—say, based on commercial driver age, given that driver aging and turnover are serious, interconnected factors with far-reaching ramifications. For a given roadway safety outcome, we can consider all connections with explanatory factors related to this outcome, implicitly or explicitly. Let us use, for example, the "more than 5 near-misses" outcome; the subnetwork built for the

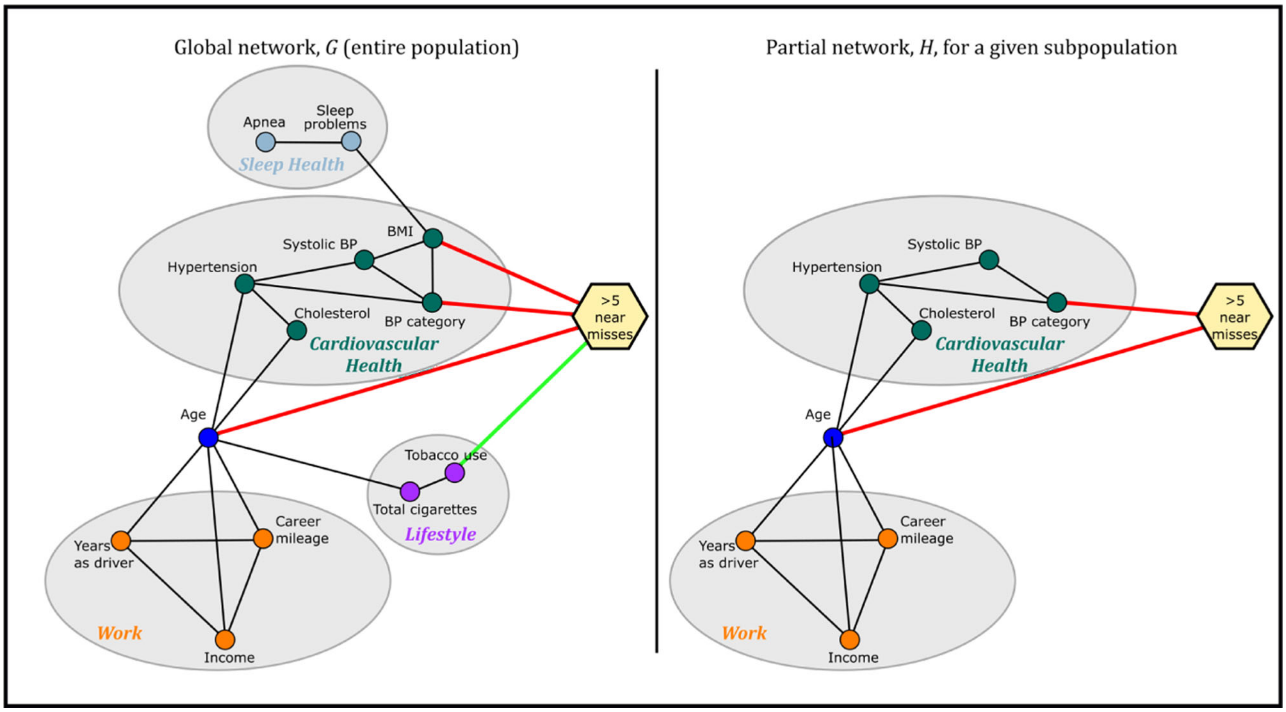

FIGURE 3 Networks built from the entire population (left) or a specific population (right); used to calculate closeness risk score.

entire commercial driver population (G) is used as a reference network. For the commercial driver subpopulation, we can build a similar network (H) by including only exposures associated with this subpopulation. Therefore (H) is a subset of (G) since many exposures will be missing. The closeness centrality (how close a node is to all other nodes in the network), C(o), for a given roadway safety outcome (e.g., o= "more than 5 near misses"), is a measure of the distance from this outcome/node to all related exposures. We calculate $C^G(o)$ for the global network and $C^H(o)$ for the subpopulation. The network topology score is the ratio $C^H(o)/C^G(o)$, which is necessarily between 0 (no risk) and 1 (highest risk) and refers to the specific roadway safety outcome. We can then repeat the calculation for all outcomes and can average the results to have a global network topology score quantifying the global roadway safety for the given subpopulation. Similarly, we can use several centralities (e.g., degree, betweenness) to calculate risk scores placing emphasis on different network topological features. These topological scores can inform us on a variety of useful characteristics, such as, for example, existence of uniform versus localized risk across various roadway safety outcomes or extent of influence between clusters of explanatory factors, among others.

Besides various metrics and methods within the broad framework of network analysis, a wide array of other analytical methods is now available and appropriate for explicating complex networks and especially the complex WLE-CD pathways. Among the most commonly used, powerful analytical approaches in exposomic contexts, are "exposome-wide association studies,"[146] which are different from hypothesis-driven methods in which one or a few factors are selected a priori and tested individually for possible associations to health-related phenotypes. Instead of focusing on one or a few predetermined exposures at a time, agnostic "exposome-wide association studies" evaluate multiple factors: (a) each factor is assessed for possible association with phenotype; (b) associations are systematically adjusted for multiplicity of comparisons; and (c) significant associations are validated against independent samples. Along these lines, recent efforts have been undertaken to develop methods to screen for interactions and test effects of combinations or to apply new frameworks (e.g., aggregated exposures, adverse outcome pathways) to examine combinatorial effects.[147]

Furthermore, there exists a wide array of other analytical methods appropriate for quantifying the health effects of complex exposure mixtures that can be used in various combinations.[148] First, there are analytical methods that search explicitly for combined linear or nonlinear effects of exposures and their interactions, such as Bayesian methods (e.g., Bayesian weighted quantile sum regression, Bayesian group index regression), the Treed Distributed Lag Mixture Models, the Multi-outcome Meshed Gaussian Processes on Projected Inputs, and others. Second, there are analytical methods that use artificial intelligence/machine learning to maximize prediction performance, such as Multilayer Perceptron, XGBoost, random forest, SVM, Elastic-net, SHAP, and others. Third, there are multistage modeling analytical methods for combined effects such as Exposure Continuum Mapping, Generalized Additive Models, Participant Component Pursuit, GAM and LASSO clustering transitions on phenotypic characteristics, and others. Fourth, there are studies employing omics data to improve inference on connections between exposome and health, using diverse methods, including bidirectional or multiomics mediation analysis, generalized linear models and triplot, unknown clustering, bipartite graph, and others. Finally, in the search of causal relationships between (especially environmental) exposures and health, causal random forests, mediation analysis, causal mediation analysis, and quantile g-computation are some commonly used methods. Last, herein we do not intend to provide an exhaustive but only an indicative catalogue of potential analytical methods to study complex exposomic contexts.

5.4 | Emerging paradigm: Turning challenges into opportunities

While still in its infancy phase, this emerging integrative paradigm in commercial driving epidemiology faces challenges, not atypical of observational, exposomic, and network research.[120,149,150] Yet, comprehensive research designs and utilization of appropriate scientific and technological innovations, along with commensurate funding, can contribute to more comprehensively tackling many of these challenges and even turning them into promising opportunities to enhance empirical research in commercial driving epidemiology.

Specifically, key challenges can be broadly grouped as follows: (a) collection of large, complex datasets with different types of exposures from diverse sources, but necessary for rigorous data analyses; (b) measurement of multiple, multidimensional, heterogeneous, and oftentimes hard to access mixtures of exposures over extended periods of time, as the exposome changes markedly over time; (c) analyses of complex heterogeneous data along disparate spatio-temporal frames requiring innovative analytical frameworks, including intricacies associated with exposome-wide association studies and network analysis that are the building blocks of the emerging paradigm; (d) assessment of causality because of confounding, reverse causation, and other uncertainties; and (e) logistical and budgetary constraints as omics applications and repeated collection of diverse biomarkers can be both expensive and logistically cumbersome.

While various "remedial" actions can largely offset these methodological, analytical, and logistical challenges, we believe that they can also be turned into opportunities for advancing commercial driving epidemiology, as even partial characterization of the WLE-CD can bring major benefits to empirical research. First, on the data collection front, mutually beneficial partnerships among unions, trucking fleets, trucking terminals, truckstop companies, relevant government agencies and nonprofit organizations, insurance firms, and researchers can facilitate the collection of quality longitudinal data, including the utilization of biobanks and existing datasets. Second, on the measurement front, a combination of proxy exposures, different methods of data collection and tools, along with novel technologies (e.g., sensors, GIS, high throughput "omics") can help identify exposure biomarkers and even allow integration of varied exposures to single measures. Third, on the analytical front, issues of high dimensionality warrant the study of the combined effects of diverse exposures and their interactions and the integration of causal pathways and high-throughput omics layers, other novel analytical methods such as mediation analysis, g-computation methods, causal random forest, and artificial intelligence/machine learning methods, along with other innovations that can make significant contributions to this end.[151,152] Fourth, on the causality front, among others, triangulation approaches (using diverse computational and statistical advances to address research questions) and involvement of novel omic technologies, combined with broad data sharing and cross-study collaborations offer opportunities to strengthen causal inference.[113] Especially when examining combinations of co-occurring exposures and varied health and safety outcomes, Bradford Hill's specificity criterion of causality is replete with reservations,[153] and may need to be revisited if evidence for combinations of WLE-CD exposures associated health and safety outcomes are realized. Finally, on the logistical and budgetary front, collaborations with other research teams, use of centralized biobanks and diverse available datasets, development and implementation of standardized protocols and operating procedures, use of high-throughput omics technologies that allow the integration of a wide range of exposure biomarkers in single measurement, data pooling from diverse sources, among others, can comprise helpful avenues.[154]

Despite potential challenges (and the inexhaustive list above), this emerging, pragmatic paradigm can clearly serve as a solid foundation for a process of actual enhancement of commercial driving epidemiology. Furthermore, foregoing steps can ultimately lead to sustainably improving commercial drivers' health and safety with far-reaching implications for broader population health, roadway safety, as well as beneficial consequences for the trucking industry, supply chains, and community economic development.

6 | TOWARD A NEW COMMERCIAL DRIVING EPIDEMIOLOGY

Prevention efforts grounded in traditional epistemologies have been overall inconsequential at the population level, with commercial drivers remaining among the unhealthiest and most underserved populations in the nation. Because prevailing epistemological approaches can only go so far, emerging integrative epistemological frameworks garnered insights from the exposome and network sciences have the potential to move the science of commercial driving epidemiology forward faster, more substantively and efficiently. Continuous development, validation, and proliferation of this emerging discourse can ultimately lead to the emergence of a new commercial driving epidemiology that adheres to scientific and technological breakthroughs and generates more accurate and thus useful results. This new commercial driving epidemiology can also inform government and corporate policies and related actions that can synergistically improve the long-term health and safety of underserved commercial drivers. Furthermore, while it is predominantly focused on North American commercial drivers, it can also have applications in the examination of the health and safety of European and Australian commercial drivers, other working populations, as well as to population health at large. Finally, this novel emerging discourse can also shed new light on the overlooked role of interdependent work and relevant nonwork factors in the study of population health.

AUTHOR CONTRIBUTIONS

Yorghos Apostolopoulos conceptualized and prepared the manuscript. Sevil Sönmez provided feedback on conceptualization and manuscript preparation. Matthew S. Thiese provided data set and overall feedback. Mubo Olufemi extracted and summarized some epidemiological data. Lazaros K. Gallos analyzed and interpreted the data and contributed to manuscript preparation.

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The authors declare that there are no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

DISCLAIMER

None

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