A Systems Thinking Approach To Road Safety: An Exploratory Study

A thesis submitted in the partial fulfilment of the requirement for the degree of

MASTERS OF PSYCHOLOGY

Submitted By

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Candidates Declaration

I hereby declare that the work presented in this thesis titled "A Systems Thinking Approach To Road Safety: An Exploratory Study" is being submitted in partial fulfillment of requirements for the award of the degree of Masters of Psychology presented in the Thapar School of Liberal Arts and Sciences, Thapar Institute of Engineering and Technology, Patiala is an authentic record of my work carried out under the supervision and guidance of Dr. Ipshita Chowdhury, Assistant Professor, Thapar School of Liberal Arts and Sciences, Thapar Institute of Engineering and Technology, Patiala and refers to other researcher's work which are duly listed in the reference section.

The matter embodied in this thesis has not formed the basis of awarding any other degree at this or any other universities.

Date: May 2026

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This is to certify that the above statement made by the student is correct and true to the best of my knowledge.

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Certificate

This is to certify that the thesis entitled "A Systems Thinking Approach To Road Safety: An Exploratory Study" is being submitted in partial fulfillment of requirements for the award of the degree of Masters of Psychology presented in the Thapar School of Liberal Arts and Sciences, Thapar Institute of Engineering and Technology, Patiala is a bonafide work carried out under the supervision of Dr. Ipshita Chowdhury, Assistant Professor, Thapar School of Liberal Arts and Sciences, Thapar Institute of Engineering and Technology, Patiala and that no part of this project has been submitted for the award of any other degree.

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Abstract

Road traffic fatalities in India exceed 150,000 annually, yet the cognitive mechanisms underlying unsafe interactions between different road user types in heterogeneous mixed traffic remain largely unexamined. This study applies Distributed Situation Awareness theory, grounded in distributed cognition, to investigate how car drivers, two-wheeler riders, and pedestrians structure and create and maintain their situational awareness while navigating shared urban road space in Patiala, Punjab, India. Thirty participants navigated a 16km route while providing concurrent think-aloud verbal protocols. Transcripts were analysed using semantic network construction and word frequency analysis in Python 3, generating structural metrics including density, diameter, and centrality for each group.

Network analysis revealed a structural gradient across groups. Car drivers produced a highly integrated network organised around infrastructure cues, two-wheeler riders showed a moderately dense network centred on gap assessment and social negotiation, and pedestrians produced a fragmented network structured around episodic crossing events. Semantic analysis further identified both shared and unique concepts across road user groups, revealing differences in the organisation of awareness. While motorised road users demonstrated overlap in networks, pedestrians exhibited distinct patterns of awareness associated with crossing, gap assessment, and interaction with traffic. The findings confirm that DSA produces coherent results in heterogeneous non-lane-based traffic and extend the framework's empirical base beyond Western contexts.

Keywords: Distributed Situation Awareness, Network analysis, System’s thinking, Cognitive compatibility, Distributed Cognition

CHAPTER 1: INTRODUCTION

1.1 Background

Road traffic injury is one of the most persistent and inequitably distributed public health problems of the contemporary world. Globally, approximately 1.35 million people die on roads each year, with low- and middle-income countries bearing over ninety percent of this burden despite accounting for roughly half of the world's registered vehicles (WHO, 2018). India sits at the centre of this disparity in a way that demands serious attention. With 153,972 road fatalities recorded in 2021, a fatality rate per registered vehicle more than four times that of high-income countries, and two-wheelers accounting for 44.5% of all deaths, India's road system produces casualties at a scale that decades of engineering investment and enforcement effort have not meaningfully reduced (MoRTH, 2023).

Existing approaches to road safety in India have been dominated by infrastructure design, junction geometry, speed management, and enforcement, interventions that address the physical and regulatory conditions of road use (IRC, 2017). While these have produced measurable improvements in specific contexts, they share a fundamental limitation: they treat road safety as a problem of individual components rather than of the interactions between them. The majority of serious crashes in India involve interactions between different road user types, car drivers, two-wheeler riders, and pedestrians sharing the same carriageway simultaneously, rather than single-vehicle failures (MoRTH, 2023). Addressing this requires understanding not just what individual road users do but how their cognitive representations of the same shared environment connect or fail to connect with each other.

1.2 Systems Thinking

Road safety research has increasingly recognised that crashes are not the product of individual failures but emerge from dysfunctional interactions between system components that are each operating within acceptable limits. Rasmussen (1997, p.183) defined the systems approach as one that recognises accidents emerge from the migration of behaviours across multiple system levels simultaneously, from government policy through regulatory frameworks and organisational management down to front-line operators. Leveson (2004) extended this through STAMP, Systems Theoretic Accident Model and Processes, reframing accidents as the result of inadequate control of safety constraints across a hierarchical system structure rather than sequential component failures.

Applied to road transport, systems thinking treats the road as a complex sociotechnical system, one in which social and technical components are so interdependent that neither can be understood in isolation (Trist and Bamforth, 1951). The physical infrastructure shapes what road users can perceive and do. McClure and Stanton (2012) demonstrated that road traffic exhibits all the characteristics of a complex sociotechnical system, constituted by non-linear interactions, open to environmental influence, and characterised by emergent behaviour. Safety in such a system is not an additive property of individual components but an emergent property of their interactions. This is precisely why reducing road fatalities in India requires frameworks capable of representing those interactions.

A Joint Cognitive System perspective, developed by Hollnagel and Woods (2005), extends this further by proposing that the meaningful unit of analysis in complex work environments is the coupled system of human agents and technological artefacts functioning together as a unified cognitive whole. In road transport this means a driver and their vehicle constitute one cognitive unit, and that unit embedded within an infrastructure of signals, markings, and other road users constitutes a larger one.

1.3 Distributed Cognition

Understanding how cognitive work is performed across this kind of system requires a theory of distributed cognition. Hutchins (1995) demonstrated through detailed study of ship navigation that cognitive processes, memory, computation, decision-making are not confined to individual minds but are distributed across people, tools, and the physical environment. The ship navigates not because any single navigator holds complete knowledge but because information is distributed across crew members and instruments, propagating through the system as representational states that are transformed from one form to another in a coordinated sequence. Safe navigation is an emergent property of this distributed system.

Hutchins (1995) identified three components of distributed cognitive systems that are fundamental to the present study. The propagation of representational states means information must flow through the system without distortion, transformed across agents and artefacts in a chain where each link depends on the previous one. External cognitive resources means artefacts hold and process information that would otherwise require internal cognitive effort from individual agents. Temporal distribution means cognitive processes extend through time, with earlier representations shaping later ones. Hutchins and Klausen (1996) extended this to airline cockpit operations, showing that individual errors were regularly caught by the distributed system before becoming dangerous because redundant representations existed across crew and instruments, the system was more reliable than any individual within it. Hazlehurst, McMullen and Gorman (2007) applied distributed cognition to healthcare, demonstrating that clinical decision-making failures occur not because clinicians are individually incompetent but because the distributed system fails to maintain compatible representations across its components.

1.4 Distributed Situation Awareness (DSA)

Distributed Situation awareness, the activated knowledge that agents hold about their environment during goal-directed activity (Stanton, 2006).

DSA proposes that in complex collaborative systems, awareness is distributed across agents, the human actors, artefacts i.e. the physical and regulatory elements that hold and communicate information and tasks which are the goal-directed activities that shape what agents attend to. The framework's critical contribution is its compatibility requirement: compatible rather than identical awareness states are what safe system operation requires. Salmon et al. (2009) formalised this through the concept of transactive SA i.e. the real-time exchange of awareness states between agents through shared artefacts, observable behaviour, and direct communication. When artefacts are present and functioning, transactive SA is efficient and reliable. When they are absent, agents must sustain coordination through direct interaction, and the compatibility of their respective schemas becomes the primary determinant of whether safe coordination occurs.

DSA has been applied across multiple safety-critical domains. Salmon et al. (2009) demonstrated in military command and control that SA was distributed across operators and artefacts in ways individual-level analysis could not capture. Stanton (2013) applied it to submarine operations, finding that safe navigation depended on compatible awareness distributed across crew and instruments. Salmon et al. (2017) found in surgical team research that compatibility failures between team members rather than individual competence failures were the primary precursor to adverse events.

1.5 Why Systems Thinking in India

Traffic in Indian cities is characterised by extreme vehicle heterogeneity where two-wheelers, autorickshaws, pedestrians, and heavy vehicles sharing the same environment simultaneously, non-lane-based flow continuously negotiated through micro-interactions, and predominantly unsignalized junctions where artefact-mediated coordination is unavailable for the majority of priority decisions (Arasan and Dhivya, 2008; Chandra and Kumar, 2003; Patil and Pawar, 2017). In this environment the artefacts that in Western road systems hold and communicate priority information, signals, markings, right-of-way rules are absent or unreliable. The coordination burden falls on agent-level interaction, and the compatibility of cognitive schemas across road users becomes the critical variable determining whether that interaction is safe.

Compatibility between road user groups in Indian mixed traffic is yet to be examined. The existing literature on SA compatibility in road transport, Walker, Stanton and Salmon (2011), Salmon et al. (2013, 2014) was conducted exclusively in western lane-based contexts with homogeneous vehicle composition and reliable artefact support i.e. proper formal functioning signals and road structure. These studies of this nature called for its generalizability in non-Western environments like India. The cognitive mechanisms through which car drivers, two-wheeler riders, and pedestrians represent and respond to each other in Indian conditions remain entirely unstudied. Given the scale of India's road fatalities and the specific concentration of those fatalities in interactions between road user types, this is a gap that demands empirical investigation.

CHAPTER 2: LITERATURE REVIEW

2.1 Road Safety as a Systems Problem

For most of the twentieth century road safety operated within a reductionist paradigm, one that treats crashes as the product of identifiable failures in individual components: the inattentive driver, the defective vehicle, the poorly designed road. Haddon's matrix, developed in the 1960s, formalised this approach by organising contributing factors across host, vehicle, and environment categories (Haddon, 1968). While productive for identifying risk factors in isolation, the matrix has a fundamental limitation that Mooren and Shuey (2024) identified explicitly: it describes components separately and has no mechanism for representing the interactions between them.

The shift away from this reductionist view began in safety science more broadly before finding its way into road safety research. Rasmussen (1997) demonstrated in nuclear and aviation safety that accidents migrate across multiple system levels simultaneously, from policy and regulation down to front-line operator behaviour, meaning that fixing the point of failure without addressing upstream conditions produces only temporary improvements. Leveson (2004) formalised this through STAMP, arguing that inadequate control of safety constraints across a hierarchical system structure is the root cause of most serious accidents, not sequential component failures. Both frameworks established a principle that would prove consequential for road safety: in complex systems, what matters is not whether individual components are functioning correctly but whether their interactions are adequately controlled.

Salmon, McClure and Stanton (2012) brought this systems perspective directly into road safety research, arguing that road traffic exhibits all the defining characteristics of a complex sociotechnical system, non-linear interactions between components, emergent behaviour that cannot be predicted from studying parts in isolation, open boundaries, and path dependence. Their analysis of road safety interventions showed that the persistent failure to achieve meaningful fatality reductions in many countries reflects a fundamental mismatch between the complexity of the road system and the reductionism of the frameworks used to analyse it. Mooren and Shuey (2024) reinforced this from a management perspective, arguing that systemic risk factors remain invisible to Haddon-style component analysis and that the kind of root-cause analysis long standard in aviation has never been meaningfully applied to road crashes. Together these arguments establish that understanding road safety requires studying the system of interactions between road users, infrastructure, and regulatory artefacts, not studying road users individually.

2.2 Roads as Sociotechnical Systems and Distributed Cognition

A sociotechnical system is one in which social and technical components are so interdependent that neither can be understood in isolation (Trist and Bamforth, 1951). Roads are sociotechnical systems precisely in this sense. The physical infrastructure i.e. road width, junction geometry, signal placement, surface quality, shapes what road users can perceive and do. Road users' network and behavioural repertoires determine whether technical components achieve their intended safety function. A traffic signal is technically capable of regulating priority at a junction. Whether it does so safely depends entirely on whether road users' networks include signal compliance as a binding expectation. In Indian traffic, Mohan (2002) documented that compliance is inconsistent and priority is routinely contested even where signals exist, a finding that illustrates precisely why technical and social components cannot be studied in isolation.

Hutchins (1995) Through study of ship navigation, showed cognitive processes, memory, computation, decision-making are not confined to individual minds but are distributed across people, tools, and the physical environment. The ship navigates not because any single navigator holds complete knowledge, but because position information, bearing measurements, route knowledge, and speed calculations are distributed across crew members and instruments, propagating through the system as representational states that are transformed from one form to another in a coordinated sequence. Thus, Safe navigation is an emergent property of this distributed system.

Three components of distributed cognitive systems that are directly relevant to road transport (Hutchins, 1995). First, the propagation of representational states i.e. information must flow through the system without distortion, transformed across agents and artefacts in a chain where each link builds on the previous one. Second, external cognitive resources, artefacts hold and process information that would otherwise require internal cognitive effort.. Third, temporal distribution, cognitive processes extend through time, with earlier representations shaping later ones.

Hutchins and Klausen (1996) extended distributed cognition to airline cockpit operations, showing that individual errors were regularly caught by the distributed system before becoming dangerous because redundant representations existed across multiple crew members and instruments. The distributed system was more reliable than any individual component. Hazlehurst, McMullen and Gorman (2007) applied it to healthcare, demonstrating that clinical decision-making failures occur not because individual clinicians are incompetent but because the distributed system fails to maintain compatible representations across its components. Both applications share the same fundamental insight that the present study applies to Indian roads: understanding system failure requires understanding the distributed cognitive system as a whole, not its individual components in isolation.

Hollnagel and Woods (2005) developed the Joint Cognitive System concept as a complementary framework, proposing that the meaningful unit of analysis in complex work environments is the coupled system of human agents and technological artefacts that function together as a unified cognitive whole. A car driver and their vehicle constitute one joint cognitive system. When the signal is removed the joint cognitive system must reorganise around available agent-level resources.

2.3 Studies on SA Compatibility

SA compatibility refers to the degree to which the awareness states held by different agents navigating a shared environment connect coherently enough to produce safe coordinated behaviour. It is a concept that emerges directly from the DSA framework, Stanton et al. (2006) argued that compatible rather than identical SA across agents is what complex collaborative systems require, and that incompatible SA between agents is a primary mechanism through which coordination failures occur. Studying SA compatibility in road transport is worthwhile because the crashes that resist individual-level explanation, particularly those involving interactions between different road user types, are precisely the crashes that incompatible distributed SA would predict. When a car driver's SA directs them to monitor infrastructure while a motorcyclist's SA directs them to exploit lateral gaps, both agents are performing adequately within their own awareness framework while simultaneously creating conditions for conflict. Neither individual SA analysis nor crash statistics alone can identify this mechanism, it requires a method capable of comparing the structure and content of awareness across groups navigating the same environment simultaneously.

The empirical examination of SA compatibility in road transport developed from a recognition that road user groups sharing physical space activate qualitatively different cognitive schemas, and that these differences are most consequential at junctions where coordination demands are highest. Walker, Stanton and Salmon (2011) conducted the foundational study in this tradition, motivated by the persistent over-representation of motorcyclists in road crash statistics in the United Kingdom, Stanton et al. (2006), they recruited six motorcyclists and six car drivers to navigate a shared urban circuit while verbalising their ongoing thoughts. Transcripts were analysed to construct SA networks for each group, enabling direct comparison of the concepts each group activated and how those concepts were structurally related. Overall concept overlap between groups was only 43.3%, falling substantially at junctions. Car drivers focused on lane positioning and infrastructure compliance. Motorcyclists focused on gap filtering and negotiating with other agents.

Salmon, Young and Cornelissen (2013) extended this work to intersection-specific compatibility, finding that motorcyclist SA regularly operated in spatial areas that fell entirely outside the scope of driver attention. This spatial mismatch, not just different concepts but different regions of the road environment being monitored, identified specific locations where the transactive SA described by Salmon et al. (2009) was structurally impossible: the motorcyclist was attending to a space the driver was not, meaning no exchange of awareness states could occur between them at precisely the moment coordination was most needed. Salmon et al. (2014) conducted the largest study to date, examining drivers, motorcyclists, and cyclists across four road environments in Melbourne, Australia. Their findings showed that while differences in network structure between groups were modest, differences in SA content were substantial and environment-dependent. At intersections, driver SA was dominated by traffic signal awareness in ways that left cyclists and motorcyclists peripherally represented, a finding they interpreted as artefact-mediated incompatibility: the signal so thoroughly organised driver SA that other agents were cognitively marginalised within it.

Evidence from adjacent methodological traditions strengthens these findings. Crundall et al. (2012) used eye-tracking to show that motorcyclists and car drivers scan identical junctions with fundamentally different visual strategies, with motorcyclists allocating significantly more attention to lateral gap opportunities and less to signals and markings. This convergence between verbal protocol and eye-tracking evidence, two independent methods producing the same substantive conclusion, supports the validity of schema-level incompatibility as a real and measurable phenomenon. Underwood et al. (2011) found comparable divergences between cyclists and drivers at lateral hazard assessment, with cyclists showing heightened sensitivity to threats that drivers systematically underweighted. Taken together, these studies establish that road user groups sharing physical space activate different cognitive schemas, that junctions are where these differences are most consequential, and that the DSA framework provides both the theoretical basis for understanding why and the analytical basis for measuring where.

2.3 Indian Road System

The Indian road environment is fundamentally different from the Western contexts in which all prior SA compatibility research has been conducted. Vehicle heterogeneity is extreme: two-wheelers account for approximately 72% of registered vehicles nationally yet share the same carriageway simultaneously with autorickshaws, cycles, pedestrians, and heavy goods vehicles spanning a tenfold range of speed capability and a twentyfold range of physical size (Arasan and Dhivya, 2008). Traffic flow is non-lane-based, Chandra and Kumar (2003) documented that Indian urban traffic behaves as a fluid rather than a structured stream, with lateral positioning continuously renegotiated through micro-interactions rather than governed by marking compliance. Kumar and Rao (2006) showed that this produces traffic density patterns with spatial clustering and gap distributions that differ qualitatively from lane-based systems.

Patil and Pawar (2017) estimated that 60 to 70 percent of urban intersections in Indian cities lack formal traffic control. Even where signals exist, Mohan (2002) documented inconsistent compliance, priority is routinely contested rather than conceded. This has a direct implication for distributed cognition: the coordination work that in Western contexts is largely externalised to artefacts must in Indian traffic be performed through agent-to-agent i.e. interaction amongst different road users, negotiation. The cognitive demands are substantially higher when compared to homogenous environments, and their success depends on the compatibility of the networks that different road users bring to that negotiation.

Maintaining situation awareness in this system demands more from individual agents than in artefact-supported environments. Without signals to externalise priority information, each agent must construct and sustain compatible SA through continuous monitoring of other agents' intentions, trajectories, and behavioural signals. For this to succeed, road users must hold not just adequate individual SA but sufficiently compatible SA across groups, their respective representations of the shared environment must connect coherently enough to produce coordinated rather than conflicting behaviour. When they do not, when a car driver's schema does not include a pedestrian as an anticipated element requiring response, or when a bike rider's gap commitment is invisible to a car driver whose schema is organised around forward-path monitoring, the transactive SA that Salmon et al. (2009) described as the mechanism of safe distributed coordination fails.

Despite the scale of India's road safety problem, existing research has been dominated by civil engineering and traffic flow modelling perspectives. Studies by the Indian Road Congress and the Central Road Research Institute have focused primarily on infrastructure design standards and capacity modelling under mixed traffic conditions (IRC, 2017). The Transportation Research and Injury Prevention Programme at IIT Delhi has produced important epidemiological work documenting crash patterns and injury severity (Gururaj, 2008; Mohan, Tiwari and Bhalla, 2006), but this work has not engaged with the cognitive mechanisms through which road users of different types fail to coordinate safely. Driver training in India remains focused on vehicle operation and regulatory knowledge rather than on understanding the behavioural and cognitive schemas of other road user types (Patel and Bhatt, 2018). The gap between what crash data shows, that interactions between different road user types account for a disproportionate share of serious casualties, and what interventions address individual driver skill and infrastructure geometry, is substantial and reflects the absence of cognitive interaction-level research in the Indian context.

CHAPTER 3: RESEARCH GAP AND OBJECTIVES

3.1 Research Gap

The existing road safety literature in India has been dominated by individually focused behavioural research documenting risk-taking, violation rates, and driver attitudes (Gururaj, 2008; Mohan, 2002). Driver training programmes in India remain focused on vehicle operation skills and regulatory knowledge rather than on understanding the cognitive schemas and behavioural patterns of other road user types (Patel and Bhatt, 2018). Neither approach addresses the interaction level, the question of whether different road users are equipped to anticipate and accommodate each other's behaviour in shared space.

Magazzù, Comelli and Marinoni (2006) demonstrated that car drivers holding motorcycle licences cause significantly fewer motorcycle-car crashes, which is strong evidence that cross-mode schema knowledge reduces conflict risk. Yet no Indian road safety programme has pursued this implication. Pedestrian behaviour at unsignalized junctions has been studied observationally (Petzoldt, 2014) but always as an isolated individual decision rather than as part of a distributed cognitive system.

Every prior DSA road transport study was conducted in Western, lane-based, predominantly signalized traffic environments. Indian mixed traffic is categorically different. Whether DSA produces meaningful findings in this environment has never been tested.

3.2 Research Objectives

Research Objective 1: To understand the road transport system in mixed traffic environments through the lens of Distributed Situation Awareness, across car drivers, two-wheeler riders, and pedestrians.

Research Objective 2: To assess whether network analysis is sensitive to detect meaningful differences in different road user groups in the Indian road environment.

CHAPTER 4: METHODOLOGY

This study was conducted in a naturalistic paradigm. Drivers were required to drive their own vehicles across a pre determined route.

4.1 What are Naturalistic Studies?

In road transport research, naturalistic driving studies involve observed vehicles being driven by participants on real roads under real traffic conditions, with data collected unobtrusively. The defining characteristic of the naturalistic paradigm is ecological validity, the study captures behaviour as it actually occurs rather than as it is performed in response to experimental demands.

The case for naturalistic methodology in road safety research was established most comprehensively by Dingus et al. (2006) through the landmark 100-Car Naturalistic Driving Study conducted by the National Highway Traffic Safety Administration. Instrumented vehicles were driven by 241 participants over approximately 2,000,000 miles of real-world driving, producing the largest naturalistic driving dataset collected at that time. The study demonstrated that driver behaviour in real traffic differed substantially and systematically from behaviour captured in simulators or structured observation studies. The ecological validity of naturalistic methodology, its capacity to capture what road users actually do rather than what they do when they know they are being tested , is therefore not merely a methodological preference but a substantive requirement for valid road safety research. Situation awareness in road transport is an ecologically grounded phenomenon. Salmon et al. (2014) argued that SA in road transport cannot be meaningfully studied outside the real environment that generates it, because the schemas activated during navigation are triggered by specific real-world cues, the sound of a horn, the visual looming of an approaching vehicle, that artificial environments reproduce poorly if at all.

Subsequent reviews of the naturalistic driving study literature have reinforced and extended this argument. Barnard et al. (2021), reviewing the methodological contributions of naturalistic studies, identified three consistent findings across the literature. First, driving behaviour is highly context-sensitive, the specific demands of real traffic activate cognitive and behavioural responses that controlled environments cannot reliably reproduce. Second, the concurrent capture of multiple data streams, vehicle kinematics, visual scene, verbal output, enables richer behavioural characterisation than single-measure approaches used in laboratory settings. Third, naturalistic studies are uniquely capable of capturing rare but safety-critical events, near-misses, conflict moments, hesitation at junctions. More recent work has validated naturalistic designs for studies focused on specific cognitive or behavioural questions, confirming that a defined route navigated once under real traffic conditions is sufficient to capture data on SA structure (Fitch et al., 2024). A naturalistic data-driven study conducted in Chennai by Mohan et al. (2022) found that driver physiological stress was significantly elevated at merge points and unsignalized locations where vehicle and pedestrian crossing occurred without formal regulation, and significantly reduced where median infrastructure and lane discipline were present. This study demonstrated that the specific features of Indian mixed traffic, merge conflicts, weak lane discipline, and the continuous presence of vulnerable road users, produce cognitive and physiological demands that are directly observable in naturalistic data but would be absent from any simulator study. The Indian road system cannot be adequately reproduced artificially.

4.2 Verbal Protocol Method

The technique requires participants to verbalise their thoughts continuously as they perform the task, externalising the representational states that would otherwise remain internal and unobservable. Stanton et al. (2013) provide a comprehensive review of verbal protocol methods in human factors research, noting that concurrent think-aloud is distinguished from other verbal methods by its requirement for real-time verbalisation rather than retrospective report, which reduces the memory reconstruction and post-hoc rationalisation that contaminate interview and questionnaire data. The concurrent protocol captures what is actually in working memory during task performance, the active schemas directing perception and behaviour rather than what participants believe or remember they were thinking. Walker et al. (2011) demonstrated that think-aloud protocols during on-road driving produce rich and analytically tractable data on the concepts underpinning situation awareness, and Kovácsová et al. (2020) confirmed that verbal protocol content at intersections closely corresponded with simultaneously observed behaviour, validating the method's ecological sensitivity.

Ericsson and Simon (1993) provided the theoretical foundation for verbal protocol analysis through their information-processing model of verbalisation, which identified three distinct levels of verbal report that differ in their validity as cognitive data. Type I verbalisation involves the direct externalisation of information that is already in a verbal or near-verbal form in working memory, the participant says what they are attending to without any additional cognitive processing. Type II verbalisation involves a translation step, information in working memory must be recoded from a non-verbal format, such as a visual or spatial representation, into verbal form before it can be externalised. This introduces a small degree of additional cognitive processing but does not substantially alter the content or sequence of the underlying thoughts. Type III verbalisation goes further as it involves explanation, justification, or elaboration of thoughts that requires additional cognitive operations beyond the simple externalisation of working memory content. Ericsson and Simon (1993) demonstrated that Type I and II verbalisations provide a relatively valid reflection of the sequence of thoughts underpinning task performance, while Type III verbalisation, requires participants to construct an account of their thinking rather than simply report it, introduces the risk of distortion.

The present study employed a naturalistic, structured on-road design with concurrent verbal protocol collection, following this established programme of research. The design rationale, participant selection, materials, procedure, and analytical approach are described in the sections below.

4.3 Research Design

The study employed a naturalistic on-road paradigm in which participants navigated a pre-defined urban circuit whilst providing concurrent verbal protocols. The naturalistic paradigm was selected in preference to a laboratory-based or simulator-based alternatives on the grounds that situation awareness is an ecologically embedded phenomenon, it is shaped by the actual perceived environment in which road users operate, including the heterogeneous vehicle mix, informal negotiation and absence of formal lane discipline that characterise Indian urban traffic.

The route covered approximately 16 km of the Patiala road and major urban roads, flyover segment, inner-city, commercial areas, and residential streets Traffic conditions included non-lane-based vehicle movement, roadside parking, pedestrian crossings, commercial activity, and varying levels of congestion. Sessions were scheduled between 08:00 and 10:00 hours on weekdays. This window was identified through pilot testing as one that produced representative mixed traffic conditions without the extreme congestion characteristic of later peak periods.

NASA–TLX and Driving Style Questionnaire (DSQ), were additionally administered as pre and post drive measures.

4.4 Participants

A total of thirty participants were recruited across three road user groups: car drivers (n = 10), two-wheeler riders (n = 10), and pedestrians (n = 10). Participants were recruited through snowball sampling. Inclusion criteria for motorised road users required a minimum of two years of driving or riding experience, a valid licence for the respective vehicle type, no involvement in a major road traffic incident in the preceding twelve months. All participants were familiar with the Patiala road environment. Table 1 presents the demographic characteristics of each group.

Road User Group	*Mean Age (SD)*	*Gender*	*Mean number of hours typically travelled per week*	*License Held*
Car Drivers	24.8 (2.6±)	6M / 4F	8.5h (2.3±)	Yes
Two-wheelers	23.9 (2.1±)	8M / 2F	11.2h (3.1±)	Yes
Pedestrians	23.6 (3.4±)	5M / 5F	4.3h (2.0±)	N/A

Table 1. Participants Demographics.

Note. Experience for pedestrians refers to years of independent urban commuting with regular road crossing. Hours per week for pedestrians refers to estimated road exposure time during walking commutes.

4.5 Materials

The route comprised urban arterial roads, a grade-separated flyover and major district road, inner city dense sections, and inner city residential roads. A description of each route segment is provided in Table 2, and the study route is presented in Figure 1.

Segment	*Road type*	*Length (approx.)*	*Speed range*
1	Major district	3.5 km	40–50 km/h
2	Urban arterial	2.5 km	40–50 km/h
3	Grade-separated	2.0 km	50–70 km/h
4	Urban arterial	2.0 km	30–40 km/h
5	Inner city	3.5 km	10–30 km/h
6	Inner city residential	2.5 km	30–40 km/h

Table 2. Route characteristics.

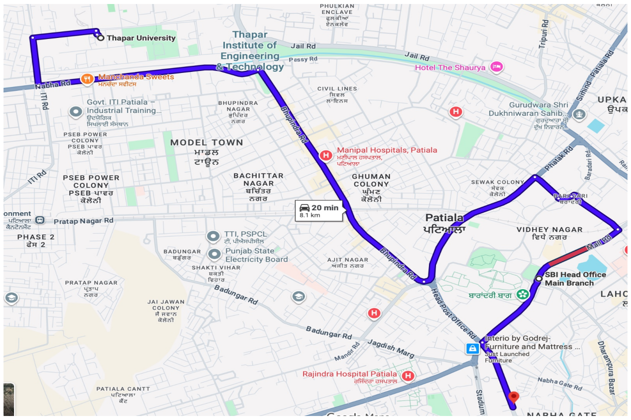


Figure1. Outward journey map

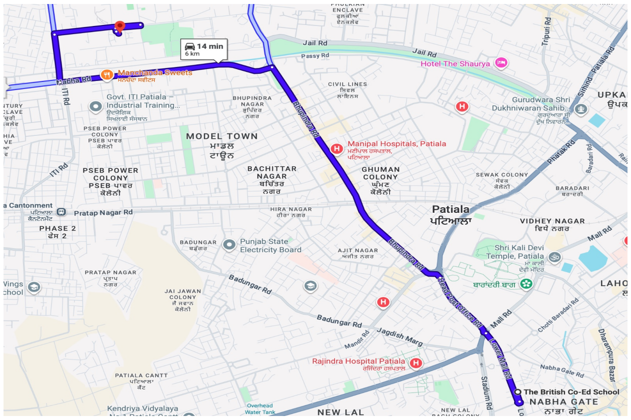


Figure2. Return Journey map

Car driver participants navigated the route in privately owned vehicles. Vehicles included the Hyundai i10, Maruti Suzuki Swift Dzire, Hyundai Verna and Maruti Suzuki Alt all were manual cars. Two-wheeler riders completed the route on their own vehicles, which included the Honda Activa, Jupiter and TVS Apache which were gearless. Pedestrians navigated the route on foot and required no vehicle instrumentation.

Verbal protocols were recorded using a lapel microphone clipped to each participant's collar. All recordings were transcribed verbatim using Microsoft Word following the completion of data collection.

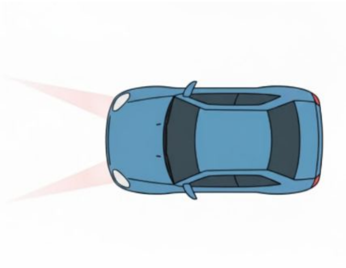
The NASA Task Load Index (NASA-TLX; Hart and Staveland 1988) was administered to all participants pre and post the completion of the route. The NASA-TLX is a multidimensional workload assessment instrument that measures perceived demand across six subscales: mental demand, physical demand, temporal demand, performance, effort and frustration. Its inclusion in the present study served purpose for assessing whether the concurrent verbal protocol task imposed an additional cognitive load on participants beyond that of the primary navigation task

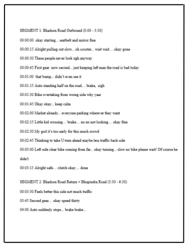
The Driving Style Questionnaire (DSQ; Reason et al. 1990) was completed by all licensed participants prior to commencing the route. The DSQ is a self-report instrument assessing driving behaviour across four dimensions, reckless/careless, anxious, angry/hostile, and patient/careful. The DSQ enabled identification of participants whose self-reported behaviour suggested systematic violation tendencies that would not be visible in licence data. If participants score high on aggressive and anxious dimensions then they were not asked to participate in the study.

4.4 Procedure

Upon arrival at the test location, participants were welcomed and they completed the informed consent form and demographic questionnaire.Following this they were provided with a written information sheet describing the study aims and procedure. Participants additionally completed the NASA-TLX workload and DSQ at this stage.

Participants drive the route
whilst providing verbal
(think aloud) protocol





SEGMENT 1: Bhadson Road Outbound (0:00 - 3:30)

00:00:00 okay starting... seatbelt and mirror fine

00:00:15 Alright pulling out slow... oh scooter... wait wait… okay gone

00:00:30 These people never look ugh anyway

00:00:45 First gear now second... just keeping left man the road is bad today

00:01:00 that bump... didn't even see it

00:01:15 Auto standing half on the road… brake, sigh

00:01:30 Bike overtaking from wrong side why yaar

00:01:45 Okay okay... keep calm

00:02:00 Market already... everyone parking wherever they want

00:02:15 Little kid crossing… brake… no no not looking… okay fine

00:02:30 My god it's too early for this much crowd

00:02:45 Thinking to take U-turn ahead maybe less traffic back side

00:03:00 Left side clear bike coming from far... okay turning... slow no bike please wait! Of course he didn't

00:03:15 Alright safe… clutch okay… done

SEGMENT 2: Bhadson Road Return + Bhupindra Road (3:30 - 6:30)

00:03:30 Feels better this side not much traffic

03:45 Second gear... okay speed thirty

04:00 Auto suddenly stops... brake brake...

Participant verbal transcript created

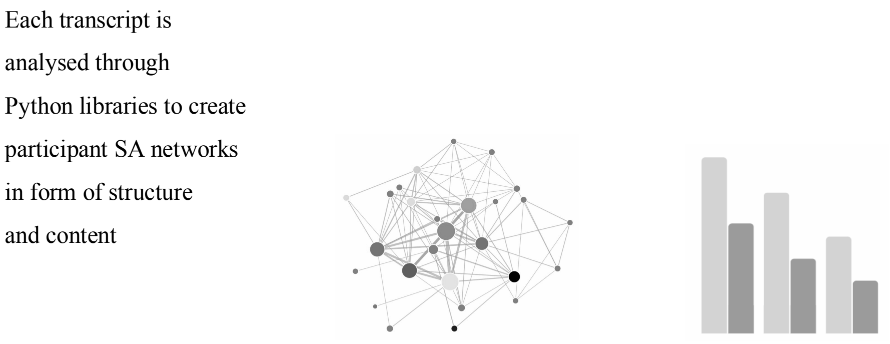


Figure 3. Analysis procedure and network construction.

Participants then received an introduction to the concurrent verbal protocol method. Participants were instructed to verbalise everything they were noticing, thinking about and deciding as they navigated the route, without pausing to reflect on or analyse their verbalisations. Following the verbal instructions, each participant completed a practice session using a short familiarisation drive or walk, during which the experimenter monitored the quality of the verbal output and provided feedback. Practice continued until the participant demonstrated sustained, continuous verbalisation before data collection commenced.

Once comfortable with both the verbal protocol procedure and the route, participants were prepared for data collection. For car driver participants, an experimenter occupied the front passenger seat throughout the drive and provided route directions where required. For two-wheeler riders and pedestrians, an experimenter followed on a separate vehicle. All participants navigated the complete 16km route whilst providing continuous verbal protocols from departure to completion. Immediately following the route, participants completed the NASA-TLX. The experimenter then conducted a brief debrief, and participants were thanked for their participation. Total session duration, including briefing, practice, data collection and debrief, ranged from approximately 55 to 65 minutes per participant.

4.5 Precautions

Participants were informed that they could discontinue participation at any point without penalty. Participants were instructed to obey all traffic regulations and prioritise safe road use over verbalisation whenever necessary. If a situation required immediate attention, participants were encouraged to focus on safe vehicle operation rather than maintaining continuous verbal output.

Data collection was scheduled during periods of typical traffic activity to ensure that participants were exposed to representative urban traffic conditions while avoiding extreme traffic conditions that could compromise safety. The selected route was pilot tested prior to data collection to confirm its suitability.

Participants were required to use their own vehicles during the study. Prior to participation, they confirmed that their vehicles were legally registered, and covered by valid insurance. This precaution was implemented to ensure compliance with road traffic regulations and to minimise potential legal or financial risks.

CHAPTER 5: RESULTS

5.1 Data Preparation and Network Construction

Network science is the study of complex systems through the mathematical representation of their components as nodes and the relationships between them as edges (Barabási, 2016). Originally developed in physics and sociology to study phenomena ranging from the spread of disease to social influence, network science has been increasingly applied in cognitive and behavioural research precisely because many cognitive phenomena, including the organisation of knowledge, the structure of mental representations, and the distribution of awareness across collaborative systems are fundamentally relational in nature. They cannot be adequately described by studying individual elements in isolation but only by examining the pattern of connections between them.

Situation awareness networks were constructed using the NetworkX library (Hagberg, Schult and Swart 2008), with visualisations generated using pyvis. In each network, nodes represent unique concepts extracted from the processed transcripts. An edge was drawn between two concepts when they co-occurred within the same utterance. Networks were constructed for each road user group to produce group-level networks for comparative structural and content analysis. For road research, Python offers robust tools to structure and analyze data. National Institutes of Health (.gov) published studies, including a healthcare data mining study that utilized open-access Python libraries to evaluate raw patient survey feedback.

5.2 Social Network Analysis: Network Structure

Network density represents the level of interconnectivity of the network in terms of links between concepts. The formula is

Network density is $\frac{2E}{N(N-1)}$ expressed as a value between 0 and 1, with 0 representing a network with no connections between concepts, and 1 representing a network in which every concept is connected to every other concept (Kakimoto et al. 2006, cited in Walker, Stanton, and Salmon 2011). It is argued that higher density values are important for situation awareness as they indicate a network in which there is greater integration of concepts than in a similar-sized network with a lower density value.

Newman (2010) defined, Network diameter was defined as the maximum shortest path distance between any two nodes in the $\max_{u,v\in V} d(u,v)$ network.The formula is

Smaller diameter values indicate that all concepts within the network are proximate to one another. Where networks contained disconnected components, diameter was recorded as undefined, reflecting fragmentation of the situation awareness structure.

Betweenness centrality was calculated for each node, identifying those concepts that lie on the greatest number of shortest paths between other concept pairs in the network. The formula is . $C_B(v) = \sum_{s\neq v\neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$ Nodes with high betweenness centrality function as bridges within the situation awareness network, their removal would disconnect otherwise connected concepts.

5.2.1 Network Structure Metrics

Network Metrics	*Car Drivers*	*Two-wheelers*	*Pedestrians*
Network Density	0.35	0.23	0.09
Clustering Coefficient	0.50	0.09	0.14
Network Diameter	Connected	Undefined	Undefined

Table 5.1. Network Structural Metrics by Road User Group

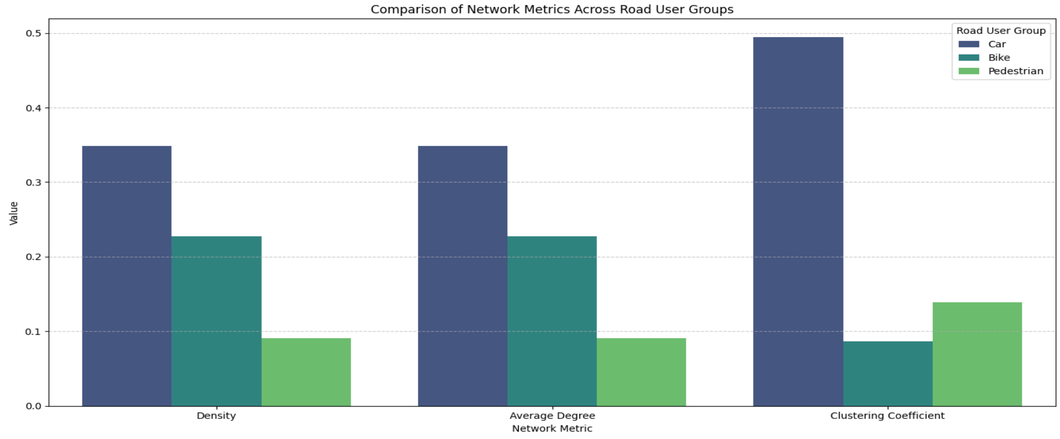


Figure 4. Bar chart comparing density, average degree, and clustering coefficient across groups

Car drivers produced the most connected network at 0.35, meaning 35% of all possible connections between concepts are present in their network. Two-wheeler riders were moderate at 0.23. Pedestrians produced the most fragmented network at 0.09, meaning only 9% of possible connections are present.

The clustering coefficient shows that car drivers show the highest clustering at 0.50, meaning that concepts connected to any given car driver concept are themselves highly likely to be connected to each other, the network forms tight local clusters. Bike riders show the lowest clustering at 0.09, indicating a more broadly dispersed network where concepts are connected across different areas rather than clustering locally. Pedestrians show a value of 0.14, which appears higher than bikes despite their lower density. This reflects that concepts cluster tightly around specific words, particularly crossing and signal, even though most concepts remain isolated.

Both the bike and pedestrian networks have undefined diameter, indicating structural fragmentation. Diameter is formally defined as max d(u,v) for all pairs u and v in V, representing the longest shortest path between any two nodes. An undefined diameter means the network is disconnected, isolated components exist that have no path to the main network. Car networks are fully connected.

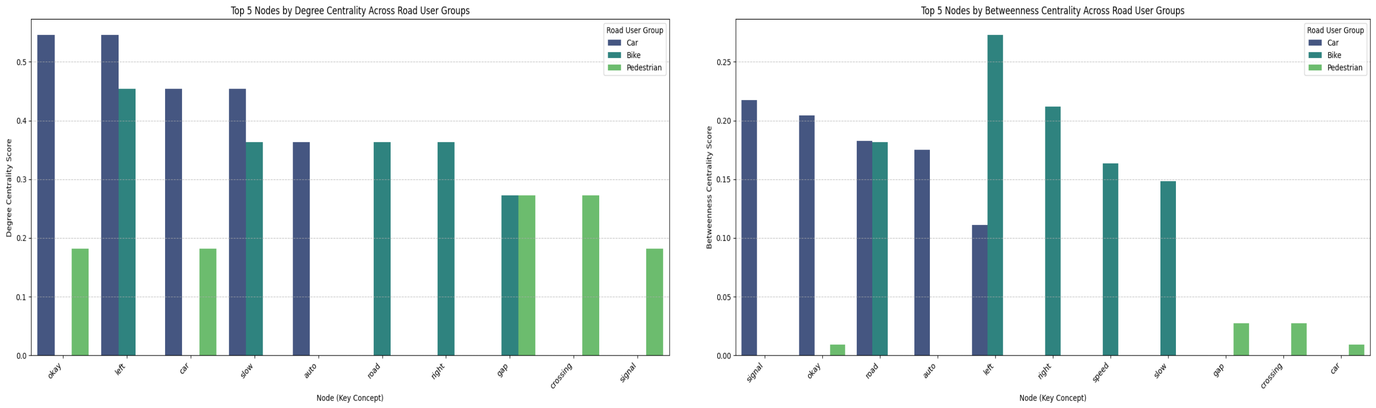


Figure 5. Two bar charts showing top 5 nodes by degree centrality and betweenness centrality across groups

5.2.2 Degree Centrality

Car drivers show ‘okay’ and ‘left’ as equal highest degree concepts at 0.55. ‘Okay’ functions as a checkpoint, co-occurring with almost every other concept. ‘Left’ at 0.55 reflects continuous positional monitoring, car drivers continuously pair ‘left’ with auto, slow, and car.

Two-wheeler riders show ‘left’ and ‘auto’ as highest degree concepts at approximately 0.45. ‘Auto’ at 0.45 for bikes reflects continuous agent monitoring.

Pedestrians show ‘gap’ and ‘crossing’ as equal highest degree concepts at 0.27.

5.2.3 Betweenness Centrality

‘Signal’ has the highest betweenness centrality for car drivers at 0.2174, indicating it plays a significant role in connecting various concepts related to driving decisions and actions.

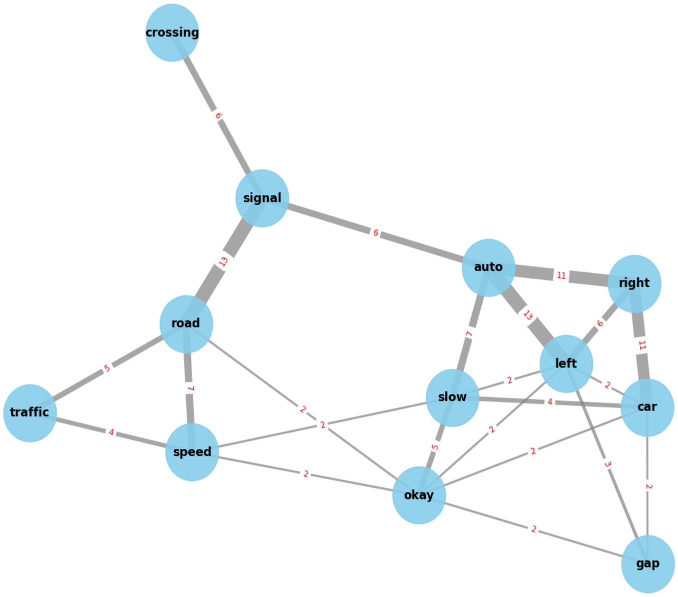
‘Left’ has the highest betweenness centrality for two-wheeler riders at 0.27. ‘Gap’ and ‘crossing’ share the highest betweenness centrality for pedestrians at 0.0273 each. Even important concepts in the pedestrian network are barely bridging. This quantifies the fragmentation visible in the semantic network. 'Okay' (0.0091) and 'car' (0.0091) also show some betweenness, but at much lower values.

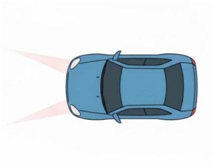
5.3 Network Content

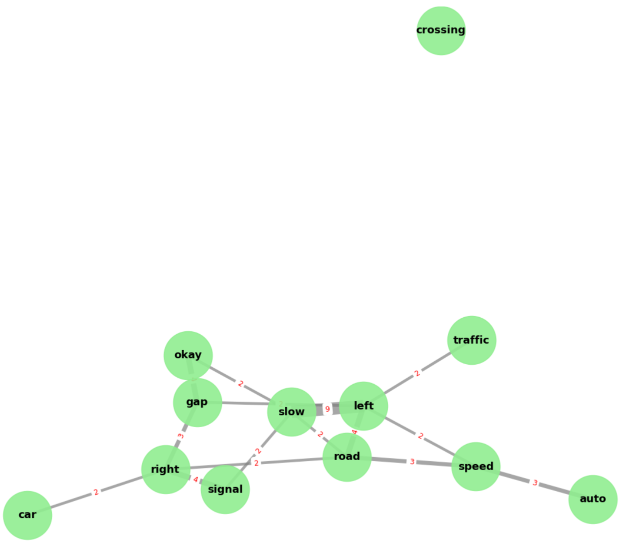
The content of road user situation awareness was examined through two procedures. First, the frequency of key concepts across road user groups was compared using the top ten most frequently occurring terms within each group's pooled transcript data. This enabled identification of the shared vocabulary present across all three road user groups. Concepts appearing consistently across all three groups were designated as common concepts and taken to represent the shared information of road user situation awareness in the traffic environment.

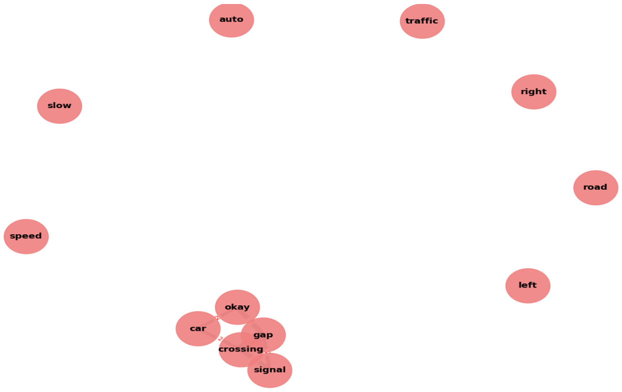
Bigram analysis was conducted as a part of semantic network analysis to examine the contextual usage of shared concepts across groups. For each concept of interest, including speed, car and auto, all two-word phrases in which the concept appeared were extracted and their frequency compared across road user groups. These words were selected because they were with highest frequency across all road user groups. The bigram illustrates how the same words with high frequency are perceived differently by different groups. This procedure enabled identification of differences in the way similar terms were used within each group's network, extending beyond simple frequency comparison to reveal differences in the structure of shared concepts.

5.3.1 Semantic Network Analysis









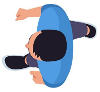


Figure 6. Semantic networks: car drivers blue, pedestrians pink, bike riders green

The car driver network is connected. ‘Signal’ occupies a prominent position, connecting to ‘road’ with a co-occurrence weight of 13, the strongest single edge in the car network, and to ‘crossing’ with a weight of 6. ‘Auto’ connects to ‘left’ with weight 13 and to ‘right’ with weight 11. ‘Okay’ connects to multiple concepts across the network. This connected structure organised around ‘signal’ as a primary bridge reflects infrastructure-mediated situation awareness.

The pedestrian network is highly fragmented. The majority of nodes, ‘slow, speed, auto, traffic, right, road, left’, are completely isolated with no edges. Only one small cluster exists, connecting ‘okay, car, gap, crossing, and signal’. Pedestrians notice the environment around them but cannot link their observations into coherent responses.

The bike rider network shows partial connectivity with one central cluster. ‘Gap, okay, slow, left, right, road, signal, speed, auto, car, and traffic’ are connected in a cluster. ‘Crossing’ floats in isolation at the top right.

5.3.2 Top Keywords of each Road User Group

Rank	Car Drivers	Freq	%	Two-Wheeler	Freq	%	Pedestrians	Freq	%
1	road	203	16.25	road	116	14.66	crossing	55	26.70
2	ahead	169	13.53	auto	87	11.00	gap	28	13.59
3	auto	143	11.45	car	83	10.49	signal	23	11.17

4	gear	120	9.61	slow	82	10.37	ill	18	8.74
5	right	116	9.29	ahead	77	9.73	people	17	8.25
6	okay	110	8.81	gap	75	9.48	car	15	7.28
7	slow	102	8.17	left	70	8.85	bike	13	6.31
8	speed	100	8.01	speed	70	8.85	still	13	6.31
9	left	95	7.61	right	67	8.47	slowed	13	6.31
10	bike	91	7.29	lane	64	8.09	signals	11	5.34

Table 5.2. Top 10 Keywords by Road User Group

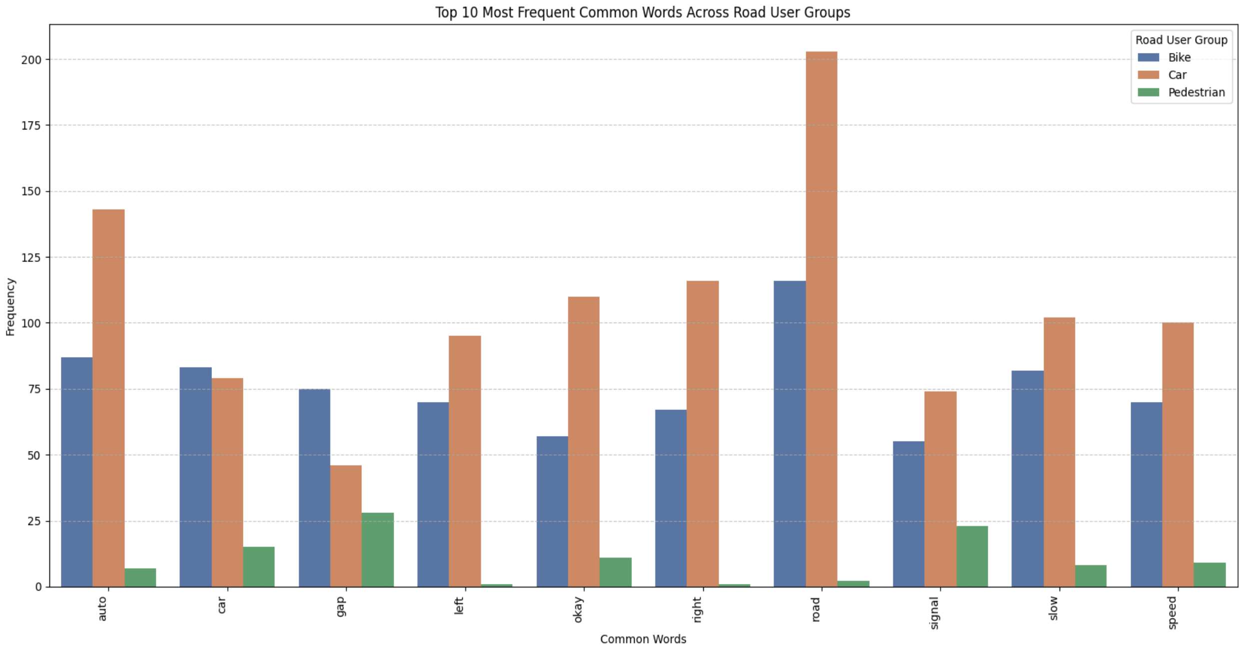


Figure 7. Grouped bar chart of top 10 common words across groups

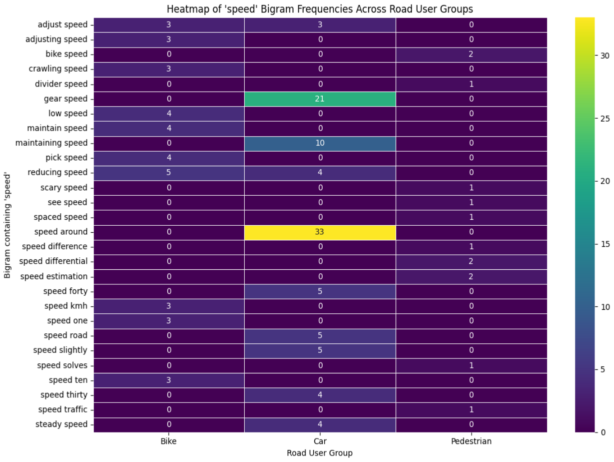
Road is the most frequent concept shared across all three groups, present in all top tens. Car drivers use ‘road’ 203 times, representing 16.25% of all car verbal output, reflecting infrastructure-oriented networks. Pedestrians use ‘road’ approximately 3 times. ‘Gap’ reveals the two-wheeler riders use ‘gap’ 75 times at 9.48% of bike output. Pedestrians use ‘gap’ 28 times at 13.59%. For car drivers it ranks lower and is not prominent in their network.

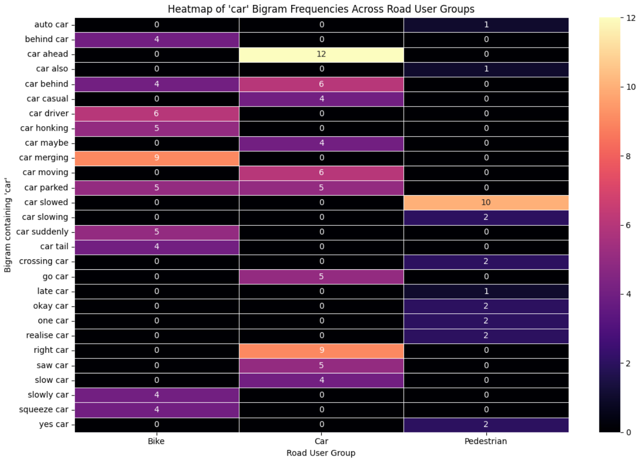
‘Gear’ appears at rank 4 for car drivers at 120 occurrences, representing 9.61% of all car verbal output. It appears in neither bike nor pedestrian top tens. ‘Gear’ is a vehicle operation concept that connects speed management to mechanical vehicle control.

‘Crossing’ dominates pedestrian output at 55 occurrences representing 26.70% of all pedestrian verbal output.

5.3.3 Bigram Analysis

Bigram analysis examined two-word consecutive phrases to reveal not just which concepts groups activate but the specific context in which shared concepts are used. Three key bigrams were analysed, speed, car, and auto.





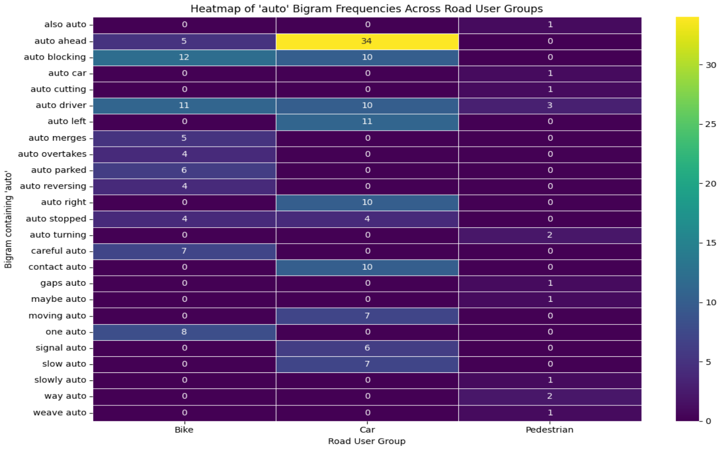


Figure 8. Three bigram heatmaps for speed, car, and auto

Speed bigrams

‘Speed around 'appears 33 times for car drivers and zero times for both other groups. Car drivers assess speed as a spatial concept relative to their surroundings, managing speed in relation to the road environment. ‘Gear speed’ appears 21 times for cars and zero for both other groups, connecting speed management to mechanical vehicle operation. Two-wheeler riders use ‘low speed’, ‘pick speed’, and ‘reducing speed’ adaptive speed responses to other agents' behaviour. Pedestrians produce almost no speed bigrams, consistent with speed being something that happens to vehicles around them rather than something they manage.

Car bigrams

‘Car ahead 'appears 12 times for car drivers and zero for both other groups, car drivers process other cars primarily as forward obstacles. ‘Car merging’ appears 9 times for bike riders and zero for both other groups, bike riders process cars as lateral agents entering their space requiring negotiation response. ‘Car slowed’ appears 10 times for pedestrians and zero for motorised groups, pedestrians watch for cars decelerating as their primary affordance signalling that crossing may be safe.

Auto bigrams

‘Auto ahead’ dominates car driver auto bigrams at 34 occurrences. Car drivers process autos primarily as forward obstacles. ‘Auto blocking’ appears 12 times for bike riders and 10 times for car drivers, reflecting that both motorised groups experience autos as blocking agents. ‘Auto driver’ appears 11 times for bike riders and 10 times for car drivers. This agent-level awareness is absent from pedestrian auto bigrams, where autos are processed as vehicles to react to rather than agents to negotiate with.

5.4 Pre-Post Measures

5.4.1 NASA-TLX Workload

The NASA-TLX was administered pre and post the on-road session as a control measure to ensure that the verbal protocol task did not impose excessive additional workload that would compromise driving performance.

Group	*Pre-Route M (SD)*	*Post-Route M (SD)*
Cars	39.92 (3.42)	51.02 (3.80)
Bikes	50.77 (4.01)	69.48 (4.07)
Pedestrian	44.65 (3.58)	60.58 (3.49)

Table 5.4 NASA Tlx Workload scores

5.4.2 Driving Style Questionnaire

The DSQ was administered pre-drive to characterise the habitual behavioural tendencies of each group. Car drivers scored highest on cautious style and lowest on high-risk. Two-wheeler riders scored highest on high-risk and angry/aggressive dimensions. Pedestrians scored highest on anxious style.

Style Dimension	**Cars M (SD)**	**Bikes M (SD)**	**Peds M (SD)**
Cautious Style	3.95 (0.25)	2.57 (0.18)	3.07 (0.16)
Anxious Style	2.65 (0.25)	3.70 (0.22)	4.30 (0.18)
Angry/Aggressive Style	2.45 (0.32)	3.90 (0.22)	3.02 (0.18)
High-Risk Style	2.23 (0.26)	4.28 (0.23)	2.71 (0.17)

Table 5.5 DSQ scores

CHAPTER 6: DISCUSSION

6.1 Does Distributed Situational Awareness Apply to Indian Mixed Traffic?

The fundamental question the study addresses is whether the Distributed Situational Awareness framework produces coherent and interpretable findings in Indian mixed traffic. The network structure results provide an answer. Car drivers produced the most interconnected situational awareness network with density 0.35, two-wheeler riders a moderate network at 0.23, and pedestrians the most fragmented at 0.09. Hutchins (1995) argued that the density of connections in a distributed cognitive system reflects the extent to which representational states can propagate effectively across the system. A network density of 0.35 for car drivers means that activating any one concept tends to activate many others simultaneously, their network is highly connected, with vehicle operation concepts, spatial awareness concepts, and agent monitoring concepts broadly interconnected. A density of 0.09 for pedestrians means the opposite, most concepts exist in isolation, unable to propagate to other concerns. Pedestrians cannot form the coordinated responses that safe navigation in mixed traffic requires because their system lacks the connectivity to support them.

The fragmentation finding is that both bike and pedestrian networks have undefined diameter while car networks are connected. An undefined diameter means isolated components exist with no path to the main network. Stanton et al. (2006) argued that compatible SA across agents requires that each agent's awareness states connect coherently with the system as a whole. A fragmented network means certain cognitive concerns are completely cut off from others. For bike riders this manifests as crossing being entirely disconnected from their negotiation cluster, and for pedestrians it manifests as vehicle speed, agent type, and road condition concepts existing as isolated nodes with no path to their crossing and gap assessment concerns. These findings are consistent with prior DSA road research in their direction while extending it in important ways. Walker et al. (2011) found that motorcyclists and car drivers produced different SA networks in

Western conditions, and Salmon et al. (2014) found that network structure showed minor but meaningful differences across road user groups in Melbourne. The Indian data replicates the finding of group-level structural differences and extends it by showing that the fragmentation effect is substantially more pronounced, particularly for pedestrians, who were not included in any prior study.

The keyword frequency analysis provides evidence that DSA applies in Indian conditions. All three groups share a common set of high-frequency concepts, ‘road, auto, gap, signal, slow, speed’ which is consistent with what Salmon et al. (2014) termed invariant concepts: shared cognitive anchors activated regardless of transport mode. The presence of these shared concepts confirms that all three groups are attending to the same fundamental categories of the road environment. However the frequency differences between groups for these shared concepts reveal the differences that Distributed Situation Awareness theory predicts. ‘Road’ appears 203 times for car drivers at 16.25% of their total verbal output, reflecting a continuous infrastructure-oriented network, the road as an environment to navigate within. For pedestrians ‘road’ appears approximately three times, reflecting an entirely different relationship: the road is a threat zone to cross rather than an infrastructure category to process. Two groups sharing the same concept but using it to represent fundamentally different cognitive concerns are the concept differences that Stanton et al. (2006) argued characterises unsafe distributed systems.

‘Gap’ presents a complementary pattern. Two-wheeler riders use ‘gap’ 75 times at 9.48% of their output. Pedestrians use ‘gap’ 28 times, representing 13.59% of their total verbal output, making it proportionally their second most prominent concept despite lower absolute frequency. For both groups gap is a survival resource, used to find entry into dominant traffic streams. For car drivers ‘gap’ ranks lower and is not structurally prominent in their network. This different activation of ‘gap’ between vulnerability-exposed groups and the dominant motorised group is consistent with Walker et al.'s (2011) finding that gap filtering is a motorcycle-specific schema in Western conditions and extends it by showing that in Indian conditions the gap schema is shared between bikes and pedestrians, reflecting a common response to navigating as an agent in a mixed traffic system.

The dominance of ‘crossing’ in pedestrian verbal output, 55 occurrences at 26.70% of all pedestrian keywords, provides a content finding. No single concept for any other group approaches this proportion of total verbal output. This quantifies the organisation of the pedestrian network around a single survival task. It is consistent with Read et al. (2021) who found that crossing was the central organiser of pedestrian SA in shared spaces, and extends their finding by providing a frequency measure that situates crossing as cognitively overwhelming in a way that other pedestrian concerns cannot approach.

The centrality findings provide the structural evidence for DSA compatibility and incompatibility across groups. ‘Signal’ having the highest betweenness centrality for car drivers at 0.2174 confirms that it is the structural bridge of car driver SA, the concept through which ‘crossing’ concerns and ‘vehicle navigation’ concerns are connected. Betweenness centrality of 0.2174 means ‘signal’ lies on 21.74% of all shortest paths between all concept pairs in the car network, making it essential to the structural integrity of car driver SA. Stanton et al. (2006) argued theoretically that artefacts actively hold SA in distributed systems. The betweenness finding provides structural evidence for this claim, the ‘signal’ is not just referenced by car drivers, it is holding their network system together.

‘Left’ having the highest betweenness at 0.27 for bike riders, the single highest betweenness value across all three groups and reveals that lateral positioning is the structural organiser of bike rider SA. It bridges ‘gap’ and ‘okay’ on one side to ‘road’, ‘speed’, and ‘auto’ on the other. This is not the same function as ‘left’ plays in car driver awareness, where it reflects lane compliance. For bike riders, ‘left’ is the concept through which gap assessment, agent monitoring, and speed management are integrated into a unified network.

The pedestrian betweenness values of 0.0273 for both ‘gap’ and ‘crossing’ is eight times lower than car driver ‘signal’ betweenness which shows the fragmentation of pedestrian SA. Even the most structurally important concepts in the pedestrian network are barely bridging. This means that the SA transactions described by Salmon et al. (2009) that are the real-time exchanges of awareness states between agents, cannot occur effectively from the pedestrian side of the interaction. Pedestrians are attempting to read and respond to motorised road users, as their frequency data shows through references to car, bike, slowed, and still, but their fragmented network means these observations cannot be integrated into the coherent coordinated responses that safe crossing in mixed traffic requires.

The bigram findings extend the centrality and frequency results by revealing not just which concepts groups activate but the specific context through which shared concepts are used. The speed bigrams illustrate this most clearly. ‘Speed around’ appearing 33 times for car drivers and zero for both other groups shows that car drivers assess speed as a spatial concept relative to their surroundings, a vehicle operation concept that is specific to car driver groups. ‘Gear speed’ at 21 for cars only connects speed to mechanical vehicle control. Two-wheeler riders use adaptive speed bigrams i.e. ‘low speed’, ‘pick speed’, ‘reducing speed’ reflecting speed as a dynamic response to other agents. These are not quantitative differences in the same network; they are qualitatively different frameworks for processing the same concept.

The car bigrams are perhaps the most theoretically significant finding in the bigram analysis. ‘Car ahead’ appearing 12 times for car drivers and zero for both other groups, ‘car merging’ appearing 9 times for bike riders only, and ‘car slowed’ appearing 10 times for pedestrians only represent three completely different cognitive relationships to the same road agent. Car drivers process other cars as forward obstacles. Bike riders process cars as lateral merging agents requiring negotiation. Pedestrians process cars as decelerating vehicles whose slowing signals crossing opportunity. Walker et al. (2011) argued that the same road situation is interpreted differently by different road user types, the car bigrams provide results for this.

6.2 Is Network Analysis Sensitive to Group Differences?

The second objective asked whether semantic network analysis, as a methodology, is sensitive enough to detect meaningful differences in SA structure and content across road user groups in Indian conditions. The results provide evidence that it is.

The most direct demonstration is the fragmentation finding. All three groups produce verbal output containing overlapping concepts. A simple frequency analysis of those concepts would show that all three groups mention ‘road’, ‘auto’, ‘gap’, and ‘signal’ suggesting broadly similar SA. Network analysis reveals that these shared concepts are organised into fundamentally different structures: a connected network for cars, fragmented networks for bikes and pedestrians, with undefined diameter in the latter two indicating isolated components. This structural difference is invisible to frequency counting and represents a qualitatively different level of analysis.

CHAPTER 7: CONCLUSION AND FUTURE RESEARCH

7.1 Summary of Findings

This study set out to examine two questions: whether the Distributed Situation Awareness framework produces coherent findings in Indian mixed traffic, and whether semantic network analysis is sensitive enough to detect meaningful SA differences across road user groups. The results address both questions clearly.

The DSA framework produces coherent, theoretically interpretable findings in Indian conditions. Walker et al. (2011) and Salmon et al. (2014), both of whom found that road user groups maintained coherent connected networks despite content differences. In the present study, bike and pedestrian networks are fragmented with undefined diameter, a level of structure absent from the Western literature, likely reflecting the absence of the artefact-mediated decisions that Western road systems provide. The distributed cognition that Hutchins (1995) documented in ship navigation and that Walker et al. (2011) identified in Western road transport is visible in Indian mixed traffic and the incompatibilities it reveals are specific, measurable, and theoretically grounded.

On the second objective, network analysis demonstrates sensitivity to structural differences. The fragmentation of bike and pedestrian networks, undefined diameter, isolated components. The distinction between pedestrian local clustering and bike rider global distribution reflects a structural difference that simple density measures would miss. The methodology is sensitive and the findings it produces are both valid and novel in the Indian context.

7.2 Practical Implications

The findings carry several practical implications for road safety in India.

The structural centrality of ‘signal’ for car drivers has infrastructure implications. Signal is not merely a traffic regulation tool for car drivers: it is the anchor of their system. This finding supports the prioritisation of signalisation at high-volume unsignalized junctions not only for traffic flow reasons but for cognitive reasons, providing the artefact-mediated coordination that car drivers depend on. The Indian Road Congress's focus on geometric junction design (IRC, 2017) should be complemented by consideration of the cognitive demands that different junction controls place on different road user groups. Road design also has a key role to play. Driver training must be redesigned as systems-level intervention not just vehicle operation.

The ‘crossing’ dominance in the pedestrian network and the fragmented pedestrian network suggest that pedestrians are already devoting the majority of their cognitive resources to the crossing task. Infrastructure that reduces the cognitive demands of crossing, median refuge islands, raised crossings, channelling devices help address the problem. Also removal of unplanned roadside parking that forces pedestrians and riders into conflict zones.

The ‘gap’ concept shared between bike riders and pedestrians suggest that both groups develop similar responses to navigating in mixed traffic. Cross-mode training that exposes car drivers to the gap-oriented networks of bike riders may reduce the differences documented in the car bigram data. Magazzù, Comelli and Marinoni (2006) found that car drivers with motorcycle experience cause significantly fewer motorcycle-car crashes.

7.3 Future Research Directions

Junction-level analysis is the most immediate priority. The present study examined overall group-level SA structure across the full route. Comparing network structure at signalized versus unsignalized junction segments specifically would test DSA theory's prediction that artefact absence shifts coordination burden to agent-level schemas. Salmon et al. (2014) identified intersections as the primary site of SA incompatibility in Western conditions. Replicating this with the signalized versus unsignalized contrast in Indian conditions, where the majority of junctions are unsignalized would substantially extend the theoretical contribution of the present study.

Gender as a moderating variable warrants dedicated investigation. The present study recruited broadly balanced gender representation in car and pedestrian groups and a predominantly male bike group. Gender was not examined as an analytical variable. Research in road safety has consistently found gender differences in risk perception and hazard assessment across multiple cultural contexts (Özkan and Lajunen, 2006). In Indian conditions specifically, female road users may navigate additional concerns, particularly female pedestrians in dense urban environments, that could produce distinct SA structures not captured in the present group-level analysis. Future research should recruit equal numbers of male and female participants within each group and examine whether the network structures reported here hold across gender.

7.4 Limitations

The sample of thirty participants, ten per group is appropriate for exploratory research of this kind and consistent with prior verbal protocol SA studies including Walker et al. (2011) who used twelve participants. However it limits the generalisability of findings to the broader Indian road user population. All participants were young adults between 18 and 26 years old, educated, characteristics that may not represent the full diversity of Indian urban road users.

A limitation of the present study was the inability to utilise the On-Board Diagnostics (OBD) data logger as originally intended. The OBD system was included to capture objective vehicle performance data, such as speed, acceleration, and braking behaviour, which could have provided an additional source of evidence to complement the verbal protocol data. However, due to technical difficulties encountered during data collection, reliable OBD data were not obtained and therefore could not be incorporated into the analysis. Future research should incorporate robust vehicle systems to allow for triangulation between cognitive, behavioural, and performance-based indicators of situation awareness.

Another limitation relates to participant experience across different road user roles. The majority of participants were recruited within a single road user category (car driver, two-wheeler rider, or pedestrian), and the study did not explicitly examine individuals with substantial experience operating in multiple roles. Road users who regularly alternate between driving, riding, and walking may develop a broader understanding of the demands and perspectives of other road users, potentially influencing the compatibility of their situation awareness.

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