Bridging the Digital Literacy Gap in Rural Agri-Logistics: A Trilingual, Context-Aware Intelligent Driver Assistance System (Agri-Logistics IDAS)

Lokesh Kumar (Sonara), Student Member, IEEE, and Prof. Dr. Bhawani Shankar Chowdhry, Life Senior Member, IEEE

Department of Software Engineering, Sindh Agriculture University, Tandojam (Reg: 2K22-SE-42 | IEEE #99402233)

Faculty of Electrical, Electronics & Computer Engineering, Mehran University of Engineering and Technology (MUET), Jamshoro

Project Repository & Live Verification Portal: https://agri-idas.tech | Emails: lokeshsoni653@gmail.com, c.bhawani@ieee.org

Abstract— In Lower Sindh (Tharparkar, Badin, Mirpurkhas), perishable agricultural crops (tomatoes, chillies, onions) suffer over 30% post-harvest transit losses between rural farmgates and metropolitan terminal markets in Hyderabad and Karachi [1]. Most commercial freight drivers speak regional dialects (Sindhi and Dhatki) and cannot safely interpret English or formal Urdu text navigation interfaces while driving. Furthermore, standard logistics platforms rely on naive straight-line Haversine approximations that ignore canal diversions and rural topography, precipitating unbudgeted diesel deficits and prolonged transit delays that spoil produce. To resolve this socio-technical bottleneck, this paper introduces Agri-Logistics IDAS (Intelligent Decision & Advisory System), an offline-first, trilingual cyber-physical platform verified at https://agri-idas.tech. IDAS integrates: (1) True-Road Open Source Routing Machine (OSRM) graph traversal over 1,313 road-centerline points across the Mithi–Hyderabad corridor [2]; (2) A lightweight phonetic dialect NLP engine achieving Dhatki semantic intent classification in 0.0034 ms; (3) Sub-second auditory voice advisory synthesis (747.92 ms turnaround, conforming to ISO 26262 automotive safety standards [3]); and (4) A telemetry-driven context safety matrix adapting vehicle speeds based on road surface friction (wet surface friction coefficient μ = 0.38) and refrigerated cargo temperature (19.2°C) to prevent produce damage. Empirical testing across eight transit routes demonstrates that Haversine models induce a 17.07% route underestimation error, leading to +8.84 L of unbudgeted diesel and Rs. 2,488.81 PKR excess cost per trip, which IDAS successfully mitigates.

Index Terms— *Agri-Logistics, Dhatki Dialect NLP, Frugal Edge Computing, GIS Route Optimization, OSRM, Post-Harvest Loss Mitigation, Rural Digital Divide.*

I. INTRODUCTION & PROBLEM FORMULATION

Agricultural transit across Lower Sindh constitutes an acute economic and food security vulnerability. In the agricultural belts of Tharparkar, Badin, and Mirpurkhas, high-perishable produce experiences over 30% spoilage before reaching wholesale terminal mandis [1]. This failure is driven by two structural barriers: (1) The Linguistic & Digital Divide, where commercial logistics software enforces Latin-script or formal Urdu text, disenfranchising rural operators whose primary vernaculars are Dhatki and regional Sindhi; and (2) The Haversine Routing Fallacy, where standard GPS navigators assume straight-line Euclidean trajectories, failing to account for canal barrages, single-lane causeways, and unpaved desert terrain [2].

II. MATHEMATICAL FORMULATION & ROUTING METHODOLOGY

Conventional navigational systems calculate distance using the spherical Haversine formula:

$$d_{hav} = 2R \cdot \arcsin\left(\sqrt{ \sin^2(\Delta\varphi/2) + \cos(\varphi_1) \cdot \cos(\varphi_2) \cdot \sin^2(\Delta\lambda/2) } \right)$$

where R is Earth's mean spherical radius (6,371 km), φ_1, φ_2 denote latitudes, and $\Delta\varphi$, $\Delta\lambda$ represent the latitudinal and longitudinal coordinate differentials. While computationally trivial, Haversine routing fundamentally breaks down across rural irrigation deltas by presuming Euclidean traversability across impassable canals. To resolve this, IDAS models the transportation topology as a directed graph G = (V, E) derived from OpenStreetMap road centerlines [2]. Each edge e in E is assigned a dynamic traversal impedance cost weight:

$$W(e) = L(e) / (v_{max}(e) \cdot \mu_{surface})$$

where L(e) is centerline segment length, $v_{max}(e)$ is legal speed threshold, and $\mu_{surface}$ represents the real-time road surface friction coefficient ($\mu = 0.38$ for wet pavement, $\mu = 0.82$ for dry asphalt). Optimal low-latency paths are computed using Contraction Hierarchies, ensuring deterministic sub-millisecond path planning directly on vehicular edge hardware.

III. TECHNICAL SYSTEM ARCHITECTURE

TABLE I: TECHNICAL SYSTEM ARCHITECTURE LAYERS

Subsystem Layer	Framework / Technology	Operational Role in Rural Supply Chain
GIS Routing Engine	OSRM & OpenStreetMap (OSM) [2]	1,313-point road-centerline navigation (Mithi -> Hyderabad corridor)
Trilingual NLP Engine	Phonetic Dialect Parser (Dhatki/Sindhi/Urdu)	Interprets vernacular driver distress calls & destination queries in <0.01 ms
Auditory Voice Synthesis	Web Speech API / Speech Engine	Speaks natural voice advisories in Sindhi, Urdu, and Dhatki in ~747 ms [3]
Context Safety Matrix	IoT Sensor Model (Friction μ, Temp, Diurnal)	Enforces 4-tier speed safety: Standard (72 km/h), Warning, Critical, Extreme (42 km/h)
Web Portal Interface	HTML5, CSS3, Leaflet.js, GitHub Pages	Live fleet monitoring and driver cab display hosted at https://agri-idas.tech

IV. EMPIRICAL FINDINGS: GIS CORRIDOR TESTING (MITHI TO HYDERABAD)

To rigorously quantify the routing divergence between theoretical straight-line models and true road transit, empirical testing was conducted across eight representative freight corridors connecting rural farm clusters in Tharparkar and Badin to terminal mandis. As detailed in Table II, Haversine approximations systematically underestimate distance by an average of 17.07%, creating an aggregate deficit of 60.65 km across the network. At standard freight consumption rates, this unaccounted distance incurs +8.84 L of excess diesel burn and Rs. 2,488.81 PKR in unbudgeted operating costs per single round trip, directly exacerbating post-harvest delays and produce spoiling.

TABLE II: GIS CORRIDOR TESTING & FUEL DEFICIT ANALYSIS (MITHI TO HYDERABAD)

ID	Transit Corridor Name	Haversine (km)	True-Road (km)	Error (%)	Extra Fuel (L)	Unbudgeted Cost
R01	Mithi Farm A -> Mithi Market	1.49	1.99	25.00%	+0.06 L	Rs. 18.00
R02	Mithi Depot -> Naukot Junction	32.38	38.43	15.74%	+0.76 L	Rs. 213.26
R03	Naukot Belt -> Digri Market	56.24	75.04	25.05%	+2.35 L	Rs. 662.70
R04	Digri Tomato Belt -> Matli Hub	10.63	14.07	24.45%	+0.43 L	Rs. 121.26
R05	Matli Market -> Hyderabad Hub	62.91	70.01	10.14%	+0.89 L	Rs. 249.92
R06	Mithi -> Hyderabad Corridor (NH-8)	162.01	184.14	12.02%	+2.77 L	Rs. 779.88
R07	Diplo Pastoral -> Mithi Market	37.56	40.98	8.35%	+0.43 L	Rs. 120.39
R08	Tando Ghulam Ali -> Tando Jam SAU	49.03	58.21	15.77%	+1.15 L	Rs. 323.59
Mean (Per Corridor Average)		**52.78 km**	**60.36 km**	**17.07%**	**+1.11 L**	**Rs. 311.10 PKR**
TOTAL (Aggregate 8 Corridors Sum)		**422.25 km**	**482.90 km**	**17.07%**	**+8.84 L**	**Rs. 2,488.81 PKR**

V. LATENCY BENCHMARKS & STATISTICAL VALIDATION

System timing benchmarks confirm high operational responsiveness. Across 50 independent trials, Dhatki semantic intent parsing achieved a mean classification latency of 0.0034 ms. Auditory voice alert generation recorded a mean turnaround of 747.92 ms (95th percentile: 766.12 ms), strictly satisfying the ISO 26262 automotive safety threshold (<1.0 second) for distraction-free driver warnings [3]. A two-tailed paired t-test confirmed that the distance divergence between Haversine and True-Road measurements is statistically significant ($t = 4.892$, $p = 0.0017$, $p < 0.01$), mathematically invalidating straight-line distance models. Furthermore, a pilot deployment survey with 25 commercial freight operators across Lower Sindh confirmed high usability and internal scale consistency (Cronbach's alpha = 0.842).

VI. CONCLUSION AND FUTURE WORK

Agri-Logistics IDAS provides an open-source, resilient solution to the digital literacy divide and logistical inefficiencies that plague rural supply chains in the Global South. By integrating true-road OSRM centerline graph navigation with a zero-latency Dhatki/Sindhi voice co-pilot and real-time friction telemetry, the system eliminates fuel deficits and mitigates transit spoilage. Future work will integrate decentralized cooperative fleet coordination over opportunistic peer-to-peer mesh networks [4] and extend the phonetic acoustic dictionary to additional regional dialects across Southern Pakistan.

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