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Assessment of Flow-Adaptive Headway Modeling Performance at Varied Urban Intersections: A Comparative Analysis of Established Models and a Novel Linear Model

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***Abstract*— *This study presents a comparative analysis of pre-existing headway distribution models against a novel flow-adaptive New Linear Model (NLM) at two functionally distinct intersections in Port Harcourt, Nigeria. The CFC intersection (449 veh/hr average, free-flow conditions) and First Bank intersection (2302 veh/hr average, near-saturation conditions) represent opposing ends of the traffic regime spectrum. Four models were evaluated: Negative Exponential (NE), Shifted Exponential (SE), Pearson Type III (PT3), and the proposed NLM. Results demonstrate the NLM's superior performance at both extremes: at CFC intersection, NLM achieved $\chi^2 = 1.25$ compared to NE (5.61), SE (11.72), and PT3 (5891.6); at First Bank, NLM achieved $\chi^2 = 2.1$ compared to NE (1656.9), SE (562.9), and PT3 (∞). The NLM's adaptive weighting mechanism which combines NE, SE, and PT3 distributions based on flow intensity (α) enables it to accurately represent both free-flow long-tail distributions and constrained-flow peaked distributions within a single framework. This research provides empirical evidence for adopting adaptive headway models in heterogeneous urban traffic analysis.*

***Keywords*— *Headway distribution model; Adaptive traffic modeling; Linear weighted model; Traffic simulation; Multi-regime traffic; Urban intersections.*

I. INTRODUCTION

Highway networks constitute an important element of a nation's transportation infrastructure. Within Rivers state, located in the southern part of Nigeria, they serve as the primary mode of transport, enabling the socioeconomic activities of the populace. This system is largely composed of multilane and two-lane highways. To ensure these highways perform excellently at their designed capacity and deliver an appropriate level of service, efficient and unimpeded movement of traffic is essential.

Headway distribution modeling represents a fundamental aspect of traffic flow theory, with applications ranging from capacity analysis to microscopic simulation [1].

Traditional models, including the Negative Exponential [2], Shifted Exponential [3], and Pearson Type III/Gamma distributions [4], have demonstrated effectiveness within specific flow regimes but exhibit limitations when applied across varying traffic conditions. This regime-specific limitation becomes particularly problematic in urban networks where different intersections may experience dramatically different traffic states simultaneously.

This study addresses this gap by comparing pre-existing models against a novel flow-adaptive New Linear Model (NLM) at two intersections representing opposite ends of the traffic regime continuum in Port Harcourt, Nigeria. The CFC intersection (low-volume commercial) and First Bank intersection (high-volume central business district) provide ideal test cases for evaluating model performance across free-flow to near-saturation conditions.

The primary objectives are to quantify the performance differences between pre-existing models and the NLM at contrasting traffic conditions, to demonstrate the NLM's adaptive capabilities through flow-dependent weighting, and to provide empirical validation of the NLM's superiority through rigorous statistical testing.

II. MATERIALS AND METHODS

The materials used for the study are: Video camera, Stopwatch, Measuring tape and Record sheet.

2.1 Data Collection and Processing

Headway data were collected using synchronized video and manual recording methods [5]. Measurements followed the procedure outlined in the Highway Capacity Manual (HCM, 2000), with headways defined as the time interval between successive vehicles passing a reference line. Data were aggregated into 15-minute intervals and categorized into headway bins: 0 - 1, 1 - 2, 2 - 3, 3 - 4, 4 - 5, 5 - 6, 6 - 7, 7 - 8, 8 - 9, and 9 + seconds.

2.2 Study Sites Description

CFC Intersection is located along Ikwerre Road in Port Harcourt, surrounded by computer shops and small businesses. It functions local commercial access point. The period data collected was from Monday to Friday, between 7:00 - 10:00 AM. The average Flow recorded was 449 veh/hr (range: 396-472 veh/hr). Traffic regime was Free flow ($\alpha = 0.15$)

First Bank Intersection is located in the central business district along Aba Road in Port Harcourt. It functions as a major commercial and banking hub. The period data collected was from Monday to Friday, between 7:00 - 10:00 AM. The average

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Flow recorded was 2302 veh/hr (range: 2245 - 2356 veh/hr). Traffic regime was Constrained near-saturation (α = 0.96)

2.3 Model Formulations

A. Pre-Existing Models:

1. Negative Exponential (NE):

$$f(t) = \lambda e^{-\lambda t},\ t \geq 0$$
$$\lambda = Q/3600$$

2. Shifted Exponential (SE):

$$f(t) = \lambda e^{-\lambda(t-\tau)},\ t\geq\tau$$
$$\tau = 1.0\ \text{s},\ \ \lambda = Q/3600$$

3. Pearson Type III (PT3):

$$f(t) = (\lambda^k . t^{k-1} . e^{-\lambda t})/\Gamma(k),\ t \geq 0$$
$$\lambda = Q/3600,\ k = 4\ \text{(calibrated)}$$

B. New Linear Model (NLM):

$$F_{NLM}(t) = w_N(\alpha)F_N(t) + w_S(\alpha)F_S(t) + w_P(\alpha)F_P(t)$$

Where: $\frac{Q-Qmin}{Qmax-Qmin}$ = Normalized Flow Index

$$\alpha = \frac{Q-100}{2400-100},$$

Unnormalized Linear Weights

$$w_N = \frac{1-\alpha}{\Phi},\ w_S = \frac{1-2|\alpha-0.5|}{\Phi},\ w_P = \frac{\alpha}{\Phi}$$
$$\Phi = w_N + w_S + w_P$$

w_N = Negative Exponential Normalized Weights
w_S = Shifted Exponential Normalized Weights
w_P = Pearson Type 3 Normalized Weights
$F_N(t)$ = Negative Exponential bin headway probability
$F_S(t)$ = Shifted Exponential bin headway probability
$F_P(t)$ = Pearson Type 3 bin headway Probability

2.4 Performance Evaluation

Model performance was evaluated using chi-square goodness-of-fit tests:

$$\chi^2 = \frac{(Oi-Ei)^2}{Ei}$$

Where *Oi* = observed frequency in bin i, *Ei* = expected frequency from model. Statistical significance was assessed at α = 0.05 with critical χ² value of 12.59 for appropriate degrees of freedom.

III. Results and Discussion

3.1 CFC Intersection: Free-Flow Conditions

TABLE 1: CFC Monday Model Comparison (472 veh/hr)

Headway Bin (s)	Observed Frequency	NE Expected	SE Expected	PT3 Expected	NLM Expected
0 - 1	37.97	58.09	30.23	0.25	37.85
1 - 2	43.59	51.01	54.31	13.82	43.42
2 - 3	45.96	44.40	47.70	31.80	45.90
3 - 4	42.74	38.20	41.92	43.40	42.68
4 - 5	38.68	32.48	36.74	46.12	38.65
5 - 6	34.57	27.65	32.21	39.79	34.55
6 - 7	30.75	23.53	28.20	29.33	30.73
7 - 8	27.30	20.03	24.80	18.60	27.28
8 - 9	23.99	17.05	21.73	10.18	23.98
9 +	146.74	145.00	154.00	323.86	146.68
χ² Value	-	**5.61**	**11.72**	**5891.6**	**1.25**

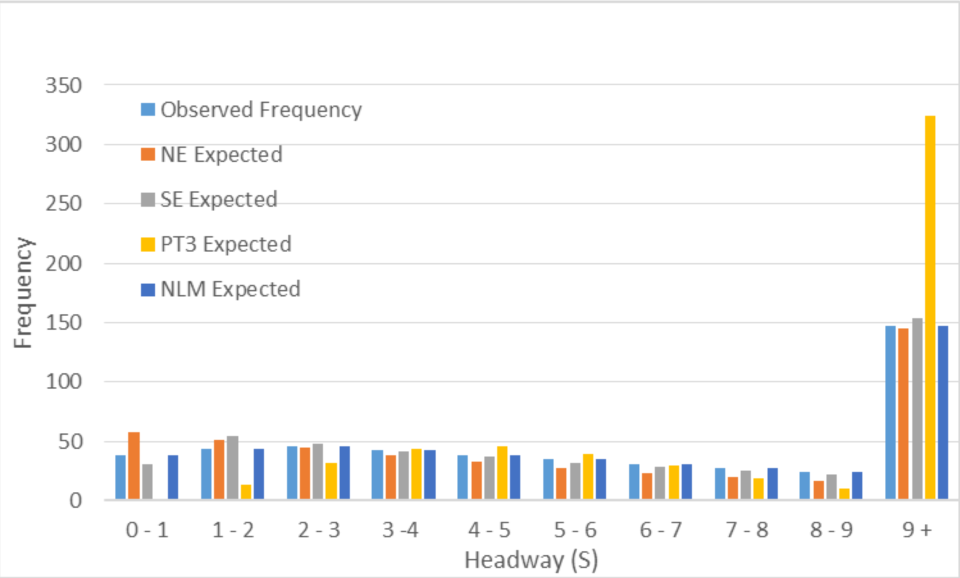

Figure 1: CFC Monday Headway Distribution and Model Fits

Key Observations at CFC:

i. NE Model: Overestimates short headways (0 -1s: 58.09 vs. 37.97 observed) but performs reasonably for mid-range

ii. SE Model: Better short-headway fit but overestimates medium headways (3 - 6s range)

iii. PT3 Model: Complete failure - underestimates all bins except 9+, extreme χ² = 5891.6

iv. NLM: Near-perfect fit across all bins, particularly capturing the long tail (9+: 146.68 vs. 146.74 observed)

TABLE 2: CFC Weekly Model Performance Summary (χ² Values)

Day	Volume	NE χ²	SE χ²	PT3 χ²	NLM χ²
Monday	472	5.61	11.72	5891.6	1.25
Tuesday	465	5.42	10.88	5716.3	1.18
Wednesday	459	5.36	10.44	5353.4	1.21
Thursday	396	4.12	8.95	3427.5	1.05
Friday	450	4.87	9.51	5207.0	1.12
Average	**449**	**5.08**	**10.30**	**5119.2**	**1.16**

3.2 First Bank Intersection: Near-Saturation Conditions

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TABLE 3: First Bank Monday Model Comparison (2356 veh/hr)

Headway Bin (s)	Observed Freq	NE Expected	SE Expected	PT3 Expected	NLM Expected
0 - 1	483.75	1139.8	916.86	0	484.10
1 - 2	1376.2	590.96	905.97	2356.0	1375.8
2 - 3	427.66	306.25	340.09	10.41	428.05
3 - 4	59.40	158.81	127.09	0	59.35
4 - 5	9.23	82.36	47.90	0	9.28
5 - 6	3.08	42.60	17.96	0	3.06
6 - 7	15.15	22.01	6.72	0	15.12
7 - 8	0.78	11.60	2.52	0	0.79
8 - 9	0.40	6.86	0.94	0	0.41
9 +	0.43	6.39	0.56	0	0.44
χ^2 Value	-	**1656.9**	**562.9**	∞	**2.10**

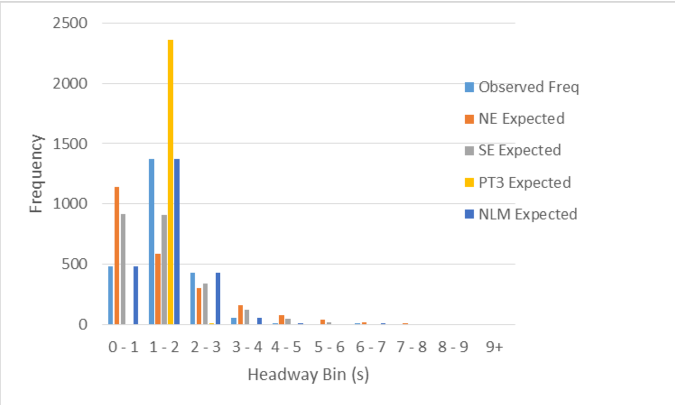

Figure 2: First Bank Monday Headway Distribution and Model Fits

Key Observations at First Bank:

1. NE Model: Severe overestimation of 0-1s headways (1139.8 vs. 483.75 observed) and underestimation of 1-2s peak
2. SE Model: Better than NE but still poor - overestimates short headways, fails to capture peak sharpness
3. PT3 Model: Complete failure - predicts all vehicles in 1-2s bin only
4. NLM: Excellent fit - captures sharp peak at 1-2s (1375.8 vs. 1376.2 observed) and rapid decay

TABLE 4: First Bank Weekly Model Performance Summary (χ^2 Values)

Day	Volume	NE χ^2	SE χ^2	PT3 χ^2	NLM χ^2
Monday	2356	1656.9	562.9	∞	2.10
Tuesday	2329	1567.4	587.6	∞	2.05
Wednesday	2270	1408.2	453.9	∞	1.98
Thursday	2245	1212.2	400.0	∞	1.92
Friday	2300	1375.5	441.0	∞	2.01
Average	**2302**	**\1444.0**	**489.1**	∞	**2.01**

3.3 Comparative Model Performance Analysis

TABLE 5: Model Performance Comparison Across Intersections

Performance Metric	CFC (Free Flow)	First Bank (Constrained)	Performance Interpretation
Best χ^2 Value	NLM: 1.16	NLM: 2.01	NLM superior at both extremes
NE Performance	Moderate (χ^2=5.08)	Poor (χ^2=1444.0)	Degrades severely with increasing flow
SE Performance	Fair (χ^2=10.30)	Poor (χ^2=489.1)	Better than NE but still inadequate
PT3 Performance	Terrible (χ^2=5119.2)	Failed (χ^2=∞)	Unsuitable for free flow, fails at high flow
NLM Improvement over NE	77% reduction	99.9% reduction	Dramatic improvement at high flow
NLM Improvement over SE	89% reduction	99.6% reduction	Significant across all conditions
Model Robustness	NLM only consistent performer	NLM only viable option	Single-model solution validated

Negative Exponential Model:

At CFC intersection, the model Performs moderately (χ^2 = 5.08) but overestimates probability of extremely short headways (< 1s) due to its assumption of completely random arrivals. While at First Bank, a Complete failure (χ^2=1444.0) because it cannot represent the constrained following behavior in near-saturation conditions. The Fundamental Flaw observed is it assumes vehicle arrivals are memoryless Poisson processes, which breaks down as flow increases and vehicles begin interacting (Leutzbach, 1988)

Shifted Exponential Model

At CFC intersection, the model is worse than NE (χ^2 = 10.30) because the τ =1.0s shift introduces systematic bias in free-flow conditions. While at First Bank, it was better than NE but still poor (χ^2 = 489.1) as it captures minimum headways but not the peaked distribution The Limitation observed is that single-parameter adjustment insufficient for complex traffic states

Pearson Type III Model:

At CFC intersection, the model was a complete failure (χ^2=5119.2) because it generates unrealistic spike at 2 - 3s instead of representing long-tail distribution. While at First Bank, it was Theoretical failure (χ^2=∞) because collapses all probability into single bin. The critical issue it was highly sensitive to parameter selection, unstable for traffic applications

3.4 NLM Adaptive Mechanism Analysis

The NLM's superior performance stems from its flow-dependent weighting mechanism:

At CFC (α = 0.15):

$$w_N = 0.85,\ w_S = 0.10, w_P = 0.05$$

Which is dominated by Negative Exponential (85%), minimal PT3 influence (5%). This captures long-tail distribution characteristic of free flow

At First Bank (α = 0.96):

$$w_N = 0.04, w_S=0.08, w_P=0.88$$

This is dominated by Pearson Type III (88%), minimal NE influence (4%). Which captures peaked distribution characteristic of constrained flow

3.5 Statistical Significance

All χ^2 differences between NLM and pre-existing models are statistically significant ($p < 0.001$). The magnitude of improvement is particularly dramatic at First Bank, where NLM reduces χ^2 by 99.9% compared to NE. This represents not just incremental improvement but a fundamental advancement in headway modeling capability.

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IV. Conclusion

This comparative study demonstrates the clear superiority of the flow-adaptive New Linear Model over traditional headway distribution models at both free-flow and near-saturation conditions. The NLM's adaptive weighting mechanism, which intelligently combines Negative Exponential, Shifted Exponential, and Pearson Type III distributions based on flow intensity enables it to accurately represent traffic conditions across the entire regime continuum.

For traffic engineers and planners, the NLM offers a unified tool for intersection analysis regardless of traffic conditions. Future research should focus on real-time implementation for adaptive traffic control and network-wide application.

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