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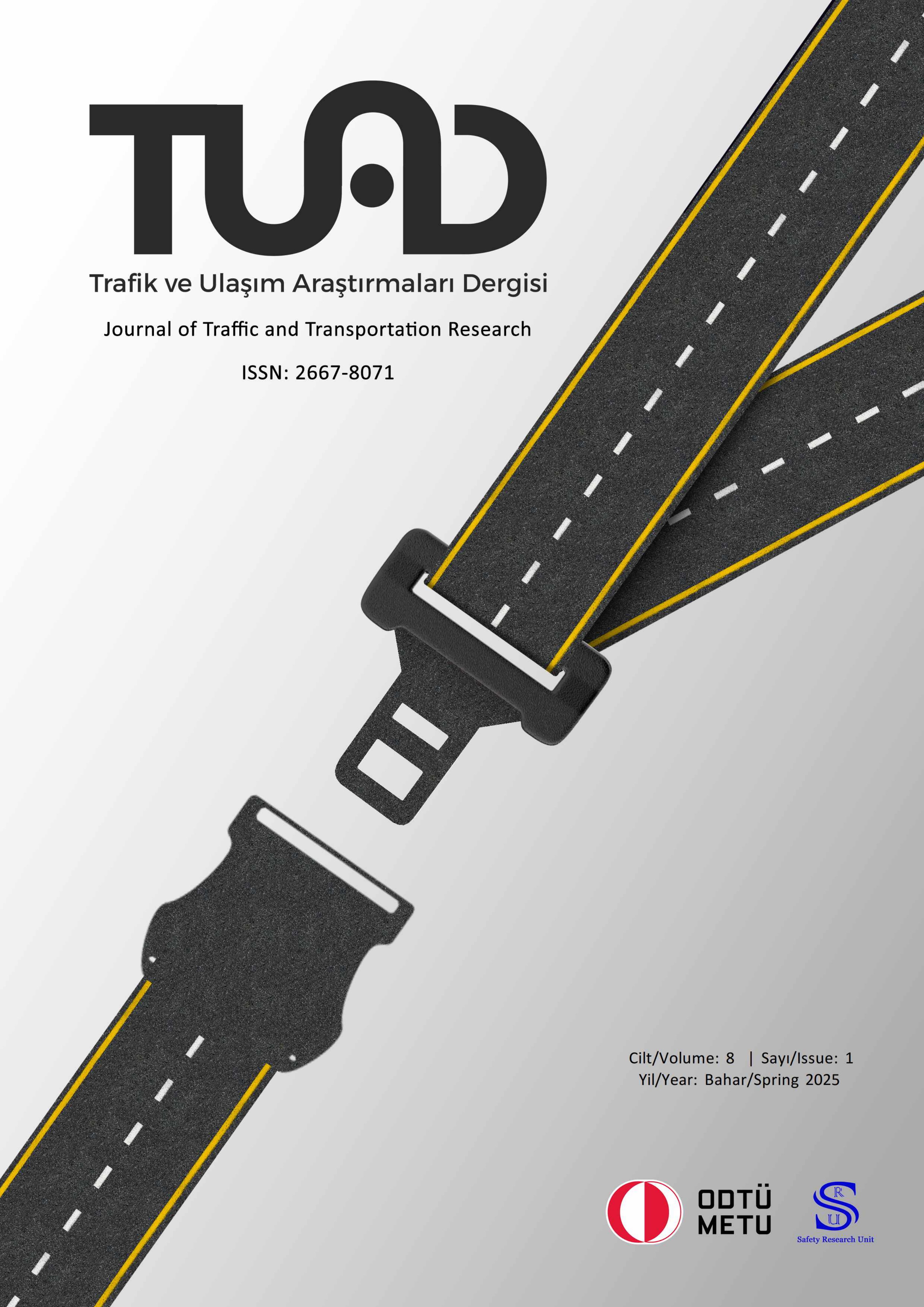

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Trafik ve Ulaşım Araştırmaları Dergisi'nin Değerli Okurları,

Dergimizin 8. Cildinin 1. Sayısını sizlerle paylaşmanın heyecanını ve mutluluğunu yaşıyoruz. 2025 yılı Bahar sayımız, farklı uzmanlık alanlarından araştırmacıların trafik güvenliği ile ilgili araştırma makalelerinden oluşmaktadır.

Bahar sayımız kapsamında dört araştırma makalesi yer almaktadır. Karlı tarafından hazırlanan ilk makalemiz, şehir içi akıllı ulaşım sistemlerinin çevresel sürdürülebilirlik perspektifinden TOPSIS analizi ile değerlendirilmesinin yapıldığı bir çalışmadır. İkinci makalemiz, Üzümcüoğlu ve Yaşar tarafından yürütülmüş, yaya ve sürücülerin agresif sürüşe tepkilerinin incelendiği bir çalışmadır. Kocabaş ve arkadaşları tarafından hazırlanmış olan üçüncü makalemiz, korna sesi ve selektörün acemi sürücülerde sürüş esansındaki psikolojik etkilerini incelemektedir. Haşıloğlu Aras tarafından hazırlanmış olan, bahar sayımızın dördüncü ve son makalesi, pandemi koşullarındaki trafik kazalarını makine öğrenmesi algoritmaları temelinde analiz eden bir çalışmadır.

2025 Bahar sayımızın sorunsuz bir şekilde tamamlanabilmesi için sürecimize destek veren tüm makale yazarlarımıza, hakemlerimize, yayın kurulu üyelerimize ve editörlerimize sonsuz teşekkürlerimi sunarım. Dördüncü cildinden itibaren TR Dizin kapsamında dizinlenmekte olan TUAD'ın yeni sayısının trafik ve ulaşım araştırmaları literatürüne ve yol güvenliği uygulamalarına anlamlı katkılarda bulunacağını umuyor; trafik ve ulaşım ortamları ile ilgili farklı disiplinlerden araştırmacıların katkılarıyla daha da zenginleşeceğini düşündüğümüz 2025 Güz sayımızda buluşana dek sağlıklı günler ve çalışmalarınızda kolaylıklar diliyorum.

Saygılarımla.

Prof. Dr. Bahar Öz

TUAD, 2025, 8(1), 1–14

Trafik ve Ulaşım Araştırmaları Dergisi

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Araştırma Makalesi | Research Article

Çevresel Sürdürülebilirlik Perspektifinden Şehir İçi Akıllı Ulaşım Sistemlerinin TOPSIS Analizi ile Değerlendirilmesi

Rukiye Gizem Öztaş Karlı[1]

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Öz

Bu çalışma, çevresel sürdürülebilirlik perspektifinden akıllı ulaşım sistemlerinin performanslarını değerlendirmek amacıyla TOPSIS (İdeal Çözüme Benzerlik ile Tercih Sıralama Tekniği) yöntemini kullanmıştır. Elektrikli otobüs sistemi (EOS), paylaşımlı elektrikli skuter sistemi (PESS), otonom araç paylaşım sistemi (OAPS) ve akıllı bisiklet paylaşım sistemi (ABPS) olmak üzere dört farklı ulaşım sistemi analiz edilmiştir. Analiz; karbon emisyonlarının azaltılması, enerji verimliliği, kaynak kullanımı, hava kalitesine etki ve yenilenebilir enerji kullanımı kriterleri doğrultusunda gerçekleştirilmiştir. Analiz sonuçlarına göre, EOS en yüksek göreceli yakınlık değeriyle en iyi performansı sergilemiştir. EOS, karbon emisyonlarının azaltılması ve enerji verimliliği konularında üstün performans göstermekte ve fosil yakıt kullanımını azaltarak kaynak kullanımını optimize etmektedir. ABPS ikinci sırada yer alarak çevre dostu bir alternatif olarak öne çıkmaktadır. OAPS üçüncü sırada yer almakta olup, enerji verimliliği ve kaynak kullanımı açısından diğer sistemlere göre daha düşük performans sergilemektedir. PESS ise en düşük performansı göstermiştir. Bulgular, şehir plancıları ve politika yapıcılar için önemli bilgiler sunmakta olup, akıllı ulaşım sistemlerinin çevresel sürdürülebilirlik hedefleri doğrultusunda en uygun seçeneklerin belirlenmesine katkı sağlamaktadır.

Anahtar Kelimeler: akıllı bisiklet paylaşım sistemi, elektrikli otobüs sistemi, otonom araç paylaşım sistemi, paylaşımlı e-skuter sistemi, TOPSIS

Evaluation of Urban Intelligent Transportation Systems from an Environmental Sustainability Perspective Using the TOPSIS Method

Abstract

This study uses the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method to evaluate the performance of intelligent transportation systems from an environmental sustainability perspective. Four different transportation systems were analyzed: electric bus system (EBS), shared electric scooter system (SESS), autonomous vehicle sharing system (AVSS) and intelligent bicycle sharing system (IBSS). The analysis was carried out in line with the criteria of carbon emission reduction, energy efficiency, resource utilization, impact on air quality and use of renewable energy. According to the analysis results, the EBS performed the best with the highest relative proximity value. EBS shows superior performance in terms of carbon emission reduction and energy efficiency, and optimizes resource use by reducing fossil fuel use. IBSS ranked second and stands out as an environmentally friendly alternative. The AVSS ranks third and performs lower than the other systems in terms of energy efficiency and resource utilization. The SESS performed the lowest. The findings provide important information for urban planners and policy makers and contribute to the identification of the most appropriate options in line with the environmental sustainability goals of intelligent transportation systems.

Keywords: intelligent bicycle sharing system, electric bus system, autonomous vehicle sharing system, shared electric scooter system, TOPSIS

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Çevresel Sürdürülebilirlik Perspektifinden Şehir İçi Akıllı Ulaşım Sistemlerinin TOPSIS Analizi ile Değerlendirilmesi

1. Giriş

Günümüzde hızla artan kentleşme ve nüfus yoğunluğu, şehir içi ulaşım sistemlerinde sürdürülebilir çözümlere olan ihtiyacı daha da belirgin hale getirmiştir. Çevresel sürdürülebilirlik, doğal kaynakların korunması, çevresel dengenin sağlanması ve ekosistemlerin korunması gibi hedefleri içeren geniş kapsamlı bir kavramdır. Çevresel sürdürülebilirlik, karbon emisyonlarının azaltılması, enerji verimliliğinin artırılması, doğal kaynakların korunması ve yenilenebilir enerji kaynaklarının kullanımının teşvik edilmesi gibi unsurları içermektedir (Camodeca ve Almici, 2021; Carter ve Rogers, 2008). Sürdürülebilir ulaşım sistemleri, kentsel alanlarda çevresel etkilerin azaltılmasına yardımcı olarak, şehirlerin gelecekte yaşanabilirliğini artırma konusunda önemli bir rol oynamaktadır.

Ulaşım sektörünün çevre üzerindeki etkileri, fosil yakıt kullanımından kaynaklanan emisyonlar ve kaynak tüketimi göz önünde bulundurulduğunda, şehirlerin sürdürülebilirlik hedeflerine ulaşmasında Akıllı Ulaşım Sistemleri (AUS) kritik bir rol oynamaktadır (Elassy vd., 2024; Öztaş Karlı ve Çelikyay, 2022). AUS, teknolojik yenilikler ve veri analizlerine dayalı çözümler sunarak trafik yönetimi, toplu taşıma ve bireysel mobiliteyi daha verimli ve sürdürülebilir hale getirmeyi amaçlamaktadır (Crawford, 2021; Tektaş ve Tektaş, 2019). Elektrikli otobüsler, paylaşımlı elektrikli skuterler, otonom araç paylaşım sistemleri ve akıllı bisiklet paylaşım sistemleri gibi farklı AUS türleri, şehirlerdeki karbon emisyonlarını azaltmak, enerji verimliliğini artırmak ve hava kalitesini iyileştirmek için kullanılmaktadır (Du ve Kommalapati, 2021; Öztaş Karlı vd., 2022; Qiu ve He, 2018).

Bu bağlamda, çevresel sürdürülebilirlik, yalnızca karbon salımını azaltmakla kalmayıp aynı zamanda enerji verimliliğini ve yenilenebilir enerji kullanımını da teşvik eden bir yaklaşımdır. Sürdürülebilir ulaşım çözümleri, toplu taşıma sistemlerinin modernizasyonu, araçlarda kullanılan yakıt türlerinin çevre dostu olması ve daha az enerji tüketen teknolojilerin geliştirilmesi gibi konuları içermektedir (Browne vd., 2012; Geels vd., 2012). Bu hedeflere ulaşmada AUS sistemlerinin uygulanması kritik bir öneme sahiptir.

Bu çalışmanın amacı, çevresel sürdürülebilirlik çerçevesinde farklı şehir içi AUS performanslarını karşılaştırmak ve bu sistemlerin çevreye olan katkılarını değerlendirmektir. Özellikle karbon emisyonlarının azaltılması, enerji verimliliği, kaynak kullanımı, hava kalitesine etki ve yenilenebilir enerji kullanımı gibi kriterler dikkate alınarak, en sürdürülebilir AUS'un belirlenmesi hedeflenmektedir. Bu amaç doğrultusunda, EOS, PESS, OAPS ve ABPS, kentsel ulaşım koşullarında TOPSIS yöntemi kullanılarak analiz edilmiştir.

Bu çalışma, AUS'un çevresel sürdürülebilirlik kriterleri açısından karşılaştırılmasına odaklanmaktadır. Literatürde, AUS'un genel faydaları ve uygulama alanları üzerine birçok çalışma yapılmış olmasına rağmen, farklı AUS türlerinin çevresel sürdürülebilirlik kriterleri açısından sistematik bir değerlendirmesi sınırlı kalmıştır. Özellikle karbon emisyonlarının azaltılması ve enerji verimliliği gibi kritik sürdürülebilirlik kriterleri göz önüne alınarak yapılacak bu değerlendirme, şehir plancıları, ulaşım plancıları ve politika yapıcılar için önemli bilgiler sunacaktır.

Araştırma kapsamında, dört farklı şehir içi ulaşım sistemi, belirlenen çevresel sürdürülebilirlik kriterleri kullanılarak TOPSIS yöntemi ile analiz edilmiştir. TOPSIS yöntemi, çeşitli alternatiflerin belirli kriterler doğrultusunda ideal çözüme olan yakınlıklarına göre sıralanmasını sağlayan Çok Kriterli Karar Verme (ÇKKV) yöntemlerinden biridir. Analiz sürecinde, uzman görüşlerine dayalı kriter ağırlıkları kullanılmıştır. Ulaşılan sonuçlar, farklı AUS türlerinin çevresel sürdürülebilirlik performanslarını karşılaştırarak en uygun sistemin belirlenmesine olanak tanımaktadır.

1.1. Akıllı Ulaşım Sistemleri (AUS)

AUS, ulaşım altyapısını ve hizmetlerini daha verimli, güvenli ve sürdürülebilir hale getirmek amacıyla bilgi ve iletişim teknolojilerini entegre eden çözümleri ifade etmektedir (Guerrero-Ibanez vd., 2015; Lin vd., 2017; Ministère de la Transition écologique et solidaire- Ministère chargé des Transports [MTES/MCT], 2017; Qi, 2008). AUS, şehir içi ulaşımda trafik yoğunluğunu azaltmak, yol güvenliğini artırmak ve çevresel etkileri en aza indirmek için yenilikçi yöntemler sunmaktadır (Barth vd., 2015; Pojani ve Stead, 2015). Teknolojiye dayalı çözümlerle AUS, şehirlerde sürdürülebilir ulaşım sistemlerinin geliştirilmesinde kritik rol oynamaktadır.

AUS; trafik yönetim sistemleri, toplu taşıma yönetim sistemleri, araç-araç ve araç-altyapı iletişim sistemleri, yolcu bilgilendirme sistemleri ve elektronik ücret toplama sistemleri gibi birçok bileşenden oluşmaktadır. Bu bileşenler, ulaşım ağının farklı parçalarını birbirine bağlayarak entegre bir sistem yaratmaktadır (Auer vd., 2016; Desertot vd., 2012). Örneğin, trafik yönetim sistemleri, sinyalizasyon ve akıllı kavşaklar yoluyla trafik akışını optimize etmekte ve trafik sıkışıklığını azaltmaktadır (De Oliveira vd., 2020; Lee ve Chiu, 2020; Zaghal vd., 2017). Bunun yanı sıra, toplu taşıma yönetim sistemleri, otobüs ve metro gibi toplu taşıma araçlarının hareketlerini izleyerek bu araçların etkinliğini artırmaktadır (Makarova vd., 2021; Welch ve Widita, 2019).

AUS ayrıca, araçlar arası iletişim ve araç-altyapı iletişim sistemleri ile kazaların azaltılmasında önemli bir rol oynamaktadır. Bu sistemler, araçlar arasında ve altyapı ile bilgi paylaşımını sağlayarak daha güvenli ve sürdürülebilir bir ulaşım ortamı yaratmaktadır (Du ve Dao, 2014; Milanes vd., 2012). Yolcu bilgilendirme sistemleri, yolculara seyahat planlama, güzergâh bilgileri ve toplu taşıma araçlarının gerçek zamanlı konumlarını sunarak, yolcuların daha bilinçli ve verimli ulaşım kararları almalarını sağlamaktadır (Akande vd., 2018; Ganesh vd. 2012). Aynı şekilde, elektronik ücret toplama sistemleri, toplu taşıma araçları, köprü ve otoyol geçiş ücretlerinin tahsilatını elektronik ortamda gerçekleştirerek, ulaşımın hızını ve verimliliğini artırmaktadır (Chandrappa vd., 2023; Lee vd., 2008).

AUS'un sunduğu faydalar, şehirlerin sürdürülebilir ulaşım hedeflerine ulaşmasında önemli rol oynamaktadır. Akıllı ulaşım çözümleri, trafik akışını optimize ederek ve alternatif güzergâh önerileri sunarak trafik sıkışıklığını azaltmaktadır (Brennand vd., 2019; Cheng vd., 2020; Uluçay ve Tanyaş, 2023). Ayrıca, bu sistemler araçların daha verimli çalışmasını sağlayarak yakıt tüketimini ve karbon emisyonlarını azaltmaktadır (Elassy vd., 2024; Lv ve Shang, 2023). Gerçek zamanlı trafik bilgileri ve akıllı sensörler, kazaların önlenmesine ve acil durum müdahalesinin hızlanmasına yardımcı olmaktadır (Cho vd., 2022; Karmakar vd., 2020). Yolculara sağlanan anlık bilgiler ve daha etkili ulaşım hizmetleri, kullanıcı memnuniyetini artırmaktadır (Brakewood ve Watkins, 2019; Tyrinopoulos ve Antoniou, 2020).

Buna ek olarak, trafikte olay yönetimi ve otoyol olay yönetim sistemleri, acil durumlar ve kazalar gibi trafikle ilgili olayların hızlıca çözülmesine yardımcı olmakta ve yolların güvenliğinin artırılmasına katkı sağlamaktadır. Bu sistemler, trafik akışını hızla eski haline getirmek ve kaza sonrası güvenlik risklerini azaltmak amacıyla gelişmiş yönetim teknikleri ve iş birliği ile çalışmaktadır (National Operations Center of Excellence [NOCoE], 2010). Yol üstyapı yönetim sistemleri, yol bakım ve onarım süreçlerini optimize ederek yolların uzun ömürlü ve güvenli olmasını sağlamaktadır. Tünel yönetim ve işletme sistemleri ise tünel içi trafiği kontrol etmek, acil durum müdahalesini hızlandırmak ve tünel güvenliğini artırmak amacıyla gelişmiş sensörler ve kontrol sistemleri kullanmaktadır (Fleming, 2009). Bu sistemler, özellikle uzun tünellerde ve yoğun trafik alanlarında güvenli bir trafik akışı sağlanmasında önemli rol oynamaktadır.

AUS'un sunduğu bu çözümler, şehirlerin ulaşım ihtiyaçlarını karşılamakla kalmayıp, sürdürülebilirlik hedeflerine ulaşmalarına da yardımcı olmaktadır. Örneğin, elektrikli otobüsler, sıfır emisyonla çalışarak çevreye duyarlı bir toplu taşıma çözümü sunmakta ve karbon emisyonlarının azalmasına katkıda bulunmaktadır (Du ve Kommalapati, 2021). Paylaşımlı elektrikli skuterler, kısa mesafeli seyahatler için sürdürülebilir bir seçenek olarak şehirlerdeki trafik yoğunluğunu ve emisyonları azaltmaktadır (Kopplin vd., 2021). Otonom araç paylaşım sistemleri, insan hatalarından kaynaklanan trafik kazalarını azaltarak güvenliği artırmakta ve aynı zamanda enerji verimliliği sağlamaktadır (Fagnant ve Kockelman, 2014). Bisiklet paylaşım sistemleri ise fosil yakıt kullanmayan, sağlıklı ve çevre dostu bir ulaşım alternatifi sunarak, bireysel araç kullanımını azaltmaktadır (Qiu ve He, 2018).

1.2. Çevresel Sürdürülebilirlik

Çevresel sürdürülebilirlik, doğal kaynakların korunması, enerji verimliliğinin artırılması, karbon emisyonlarının azaltılması ve hava kalitesinin iyileştirilmesi gibi unsurları içeren geniş kapsamlı bir kavramdır (Camodeca ve Almici, 2021; Elassy vd., 2024). Özellikle ulaşım sektörü, fosil yakıt kullanımı nedeniyle küresel karbon emisyonlarının %25'inden sorumlu olup, çevresel sürdürülebilirlik için büyük bir tehdit oluşturmaktadır (Camodeca ve Almici, 2021). Bu bağlamda, şehirlerin sürdürülebilirlik hedeflerine ulaşmalarında AUS önemli bir çözüm olarak öne çıkmaktadır.

AUS, fosil yakıt kullanımını azaltan, enerji verimliliğini artıran ve doğal kaynakların daha etkin kullanımını sağlayan çözümler sunmaktadır (Barth vd., 2015). Örneğin, elektrikli otobüsler, sıfır emisyonla çalışarak şehirlerde hava kalitesini iyileştirmekte ve karbon salımını azaltmaktadır (Du ve Kommalapati, 2021). Benzer şekilde, bisiklet paylaşım sistemleri ve paylaşımlı elektrikli skuterler, bireysel araç kullanımını azaltarak karbon emisyonlarını düşürmekte ve şehir içi ulaşımda çevre dostu alternatifler sunmaktadır (Kopplin vd., 2021).

Çevresel sürdürülebilirlik açısından AUS, karbon emisyonlarını düşürme ve enerji verimliliğini artırma potansiyeli taşımaktadır. Trafik yönetim sistemleri, şehirlerde trafik akışını optimize ederek dur-kalk trafik yoğunluğunu ve dolayısıyla enerji israfını azaltmakta, bu da hem karbon salımını hem de yakıt tüketimini düşürmektedir (Brennand vd., 2019; Cheng vd., 2020). Ayrıca, toplu taşıma yönetim sistemleri toplu taşımanın daha etkin kullanılmasını sağlayarak, fosil yakıt tüketimini azaltmakta ve enerji verimliliğini artırmaktadır (Makarova vd., 2021).

Ulaşım literatüründe, AUS'un çevresel sürdürülebilirlik açısından büyük bir potansiyele sahip olduğu ve şehirlerin sürdürülebilirlik hedeflerine ulaşmalarında kritik bir rol oynadığı sıkça vurgulanmaktadır. Barth ve diğerleri (2015), AUS'un trafik akışını iyileştirerek karbon emisyonlarını %20 oranında azaltabileceğini ortaya koymuştur. Aynı şekilde, Cheng ve diğerleri (2020), AUS'un enerji verimliliğini artırarak fosil yakıt kullanımını büyük ölçüde düşürebileceğini belirtmektedir. Bu nedenle, AUS'un yaygınlaşması, şehirlerin çevresel etkilerini azaltarak sürdürülebilir ulaşım hedeflerine ulaşmalarında önemli bir adım olarak değerlendirilmektedir.

Bu çalışma, AUS'un çevresel sürdürülebilirlik kriterlerine göre performanslarını analiz ederek literatüre katkı sağlamayı hedeflemektedir. Çalışmanın sonuçları, şehir plancıları, ulaşım plancıları ve politika yapıcılar için AUS'un çevresel etkilerini daha iyi anlamalarını sağlayacak ve sürdürülebilir ulaşım stratejilerinin geliştirilmesine katkıda bulunacaktır. AUS'un sunduğu çözümler, sadece yerel düzeyde değil, küresel ölçekte de büyük çevresel faydalar yaratma potansiyeline sahiptir.

2. Yöntem

Bu çalışmada, farklı şehir içi akıllı ulaşım sistemlerinin çevresel sürdürülebilirlik açısından değerlendirilmesi amacıyla TOPSIS yöntemi kullanılmıştır. TOPSIS, ilk olarak 1981 yılında Ching-Lai Hwang ve Yoon tarafından geliştirilen bir ÇKKV yöntemidir (Aslan vd. 2015; Urfalıoğlu ve Genç, 2013). TOPSIS, alternatiflerin ideal ve negatif-ideal çözümlere olan benzerliklerine dayanarak sıralama yapmakta, bu da her bir alternatifin en iyi ve en kötü potansiyel durumları göz önünde bulundurarak kapsamlı bir değerlendirme sağlamaktadır (Bhaskar vd. 2021; Kamalakannan vd. 2020).

Diğer ÇKKV yöntemleri yerine TOPSIS yönteminin tercih edilmesinin dört nedeni bulunmaktadır. Bunlardan ilki karşılaştırmalı analiz kolaylığıdır. TOPSIS, alternatifleri birbirleriyle değil, ideal çözüme olan yakınlıklarına göre değerlendirmektedir. Bu yaklaşım, alternatifler arasındaki farklılıkları net bir şekilde ortaya koymakta ve daha objektif bir karşılaştırma sağlamaktadır (Hwang ve Yoon, 1981; Opricovic ve Tzeng, 2004). İkincisi anlaşılması ve uygulanması kolay bir yöntemdir. TOPSIS yöntemi, diğer çok kriterli karar verme yöntemlerine göre daha anlaşılır ve uygulaması daha basittir (Chen ve Hwang, 1992). Bu, araştırma sonuçlarının hem akademik hem de pratik açıdan kolaylıkla yorumlanabilmesini sağlamaktadır. Üçüncü neden ise etkili sonuçlar vermesidir. TOPSIS, hem ideal hem de negatif-ideal çözümlere göre uzaklıkları hesaplayarak çalıştığı için kriterler arasındaki göreceli önemi ve alternatiflerin bu kriterlerdeki performansını dengeli bir şekilde değerlendirmektedir (Shih vd., 2007). Son olarak ise kabul görme düzeyi oldukça yüksektir. TOPSIS yöntemi, farklı sektörlerde ve karar verme problemlerinde geniş bir kullanım alanına sahiptir (Behzadian vd., 2012). Bu da yöntemin güvenilirliğini ve uygulanabilirliğini artırmaktadır.

Çalışmada EOS, PESS, OAPS ve ABPS olmak üzere 4 farklı şehir içi akıllı ulaşım sistemi değerlendirilmiştir. Literatür taraması sonucunda dört farklı akıllı ulaşım sistemini çevresel sürdürülebilirlik açısından değerlendirmek için önerilen kriterler ve değerler Tablo 1'de verilmiştir. Kriter değerlerinin belirlenmesinde ABD Çevre Koruma Ajansı, Avrupa Çevre Ajansı, Uluslararası Enerji Ajansı, Birleşmiş Milletler Çevre Programı, McKinsey & Company, Uluslararası Taşımacılık Forumu, Ulusal Yenilenebilir Enerji Laboratuvarı, Ulaşım Araştırma Kurulu ve UC Davis Ulaşım Çalışmaları Enstitüsü'nün raporlarından faydalanılmıştır. Analiz süreci, belirlenen kriterler doğrultusunda sistemlerin performansını karşılaştırmayı hedeflemektedir. Çalışmada kullanılan kriterler, fayda yönlü ve maliyet yönlü olarak ikiye ayrılmaktadır. Fayda yönlü kriterlerde, yüksek değerler sistemin daha iyi performans gösterdiğini ifade ederken, maliyet yönlü kriterlerde düşük değerler tercih edilmektedir. Bu çerçevede, karbon emisyonlarının azaltılması, enerji verimliliği, hava kalitesine etki ve yenilenebilir enerji kullanımı fayda yönlü kriterler olarak tanımlanmış, kaynak kullanımı ise maliyet yönlü kriter olarak belirlenmiştir. Kriterlerin detayları ve yönleri Tablo 1'de verilmiştir.

Kriterlerin ağırlıklarının belirlenmesinde uzman görüşlerine başvurulmuştur. Uzmanlara, Excel formatında ikili karşılaştırma matrisleri e-posta yoluyla iletilmiştir. Uzmanlar, bu matrisleri doldurarak, belirlenen kriterlerin karşılaştırmalı ağırlıklarını belirlemişlerdir. Toplanan bu veriler daha sonra analiz sürecinde kullanılmıştır.

Kriter ağırlıklarının belirlenmesinde, üç farklı uzmanın görüşleri alınmıştır. En az 15 yıllık deneyime sahip bu uzmanlardan biri çevresel sürdürülebilirlik ve enerji yönetimi alanında, diğeri ulaştırma politikaları üzerine çalışan bir akademisyen, üçüncüsü ise ulaştırma sistemleri planlaması ve şehir içi ulaşım altyapısı konusunda sektörde deneyime sahip bir profesyoneldir. Bu farklı uzmanlık alanları, değerlendirmede daha geniş bir bakış açısı sunarak kriterlerin dengeli bir şekilde ele alınmasını sağlamıştır.

Literatürde benzer çalışmalar, uzman sayısının 3 ile 5 arasında olmasının yeterli olduğunu bildirmektedir (Liu vd., 2012; Pathak vd. 2020). Özellikle, Saaty (1980) ve Ishizaka ve Labib (2011) tarafından yapılan çalışmalarda, çok kriterli karar verme yöntemlerinde uzman sayısının küçük tutulmasının yeterli olduğu ve bu sayede daha hızlı ve etkili sonuçlar elde edilebileceği belirtilmiştir. Bu doğrultuda, çalışmamızda üç uzmanın görüşleri, analizin güvenilirliği ve geçerliliği açısından yeterli kabul edilmiştir. Uzmanların kriterlere verdikleri ağırlıklar ortalamaları alınarak belirlenmiştir (Tablo 2). Bu ağırlıklar, TOPSIS analizinde kullanılarak her bir ulaşım sisteminin çevresel sürdürülebilirlik performansı değerlendirilecektir.

Tablo 1. Çevresel sürdürülebilirlik kriterleri ve değerleri

Kriterler	Açıklama	EOS	PESS	OAPS	ABPS	Yön
Karbon Emisyonlarının Azaltılması	Ulaşım sisteminin karbon emisyonlarını ne kadar azalttığını ifade eder. Birim: Yıllık CO_2 azaltımı (Ton CO_2/yıl).	2000	1500	1800	2200	Fayda yönlü
Enerji Verimliliği	Ulaşım sisteminin enerji verimliliği. Birim: km/kWh.	5,5	6,0	5,8	6,2	Fayda yönlü
Kaynak Kullanımı	Ulaşım sisteminin doğal kaynakları (örneğin fosil yakıtlar) ne kadar verimli kullandığını ifade eder. Birim: Yıllık doğal kaynak tüketimi (MJ/yıl).	8000	7500	7800	7200	Maliyet yönlü
Hava Kalitesine Etki	Ulaşım sisteminin hava kalitesini ne kadar iyileştirdiği. Birim: Hacim başına PM2.5 azaltımı (mikrogram/m^3).	15	12	14	16	Fayda yönlü
Yenilenebilir Enerji Kullanımı	Ulaşım sisteminin yenilenebilir enerji kaynaklarını ne kadar kullandığı. Birim: Yenilenebilir enerji kullanım oranı %	30	25	35	40	Fayda yönlü

Tablo 2. Kriter bazında uzman görüşlerinin ağırlıkları

Kriterler	Uzman 1	Uzman 2	Uzman 3	Ortalama
Karbon Emisyonlarının Azaltılması	0,35	0,30	0,25	0,30
Enerji Verimliliği	0,30	0,25	0,25	0,27
Kaynak Kullanımı	0,15	0,15	0,15	0,15
Hava Kalitesine Etki	0,10	0,20	0,15	0,15
Yenilenebilir Enerji Kullanımı	0,10	0,10	0,20	0,13

TOPSIS yönteminin uygulama adımları aşağıda özetlenmiştir (Özkan ve Deliktaş, 2020):

Adım 1: Karar matrisinin oluşturulması

Uzmanların görüşleri doğrultusunda, araştırmacı tarafından oluşturulan karar matrisinde; satırlarda üstünlüklerine göre sıralanmak istenen karar noktalarını gösterirken sütunlarda ise karar vermede kullanılacak değerlendirme faktörleri yer alır (Yurdakul ve İç, 2003). Karar matrisi eşitlik (1)'de gösterilmiştir.

A_{ij} matrisinde m karar noktası sayısını, p değerlendirme faktörü sayısını verir.

$$A_{ij}=\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1p} \\ a_{21} & a_{22} & \dots & a_{2p} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ a_{m1} & a_{m2} & \dots & a_{mp} \end{bmatrix} \quad (1)$$

Adım 2: Normalizasyon

Normalize edilmiş karar matrisinin oluşturulmasında ilk olarak her bir a_{ij} değerlerinin $(a_{11,}\, a_{21}, a_{31} \dots a_{m1})$ kareleri alınarak bu değerlerin toplamından oluşan sütun toplamları bulunur. Daha sonra her bir a_{ij} değeri ait olduğu sütun toplamının kareköküne bölünerek normalizasyon işlemi yapılır (Yurdakul ve İç, 2003).

$$N_{ij}=\frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^{2}}}(i = 1, \dots., m \ ve \ j = 1, \dots., n) \quad (2)$$

Bu işlemden sonra eşitlik (3)'teki normalize matris elde edilir.

$$N_{ij}=\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1p} \\ a_{21} & a_{22} & \dots & a_{2p} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ n_{m1} & n_{m2} & \dots & n_{mp} \end{bmatrix} \quad (3)$$

Adım 3: Ağırlıklı normalleştirilmiş karar matrisinin hesaplanması

Normalize edilmiş matrisin her bir değeri w_{ij} gibi bir değerle ağırlıklandırılması yapılır. Burada w_{ij} ağırlık değerlerinin toplamı 1 olmalıdır. Başka bir ifadeyle $\sum_{i=1}^{n} w_1$=1'dir. Daha sonra elde edilen n_{ij} değerleri w_{ij} ağırlıkları ile çarpılarak eşitlik (4)'te belirtilen ağırlıklandırılmış normalize matris bulunur (Yurdakul ve İç, 2003).

$$V_{ij}=\begin{bmatrix} w_1 n_{11} & w_2 n_{12} & \dots & w_p n_{1p} \\ w_1 n_{21} & w_2 n_{22} & \dots & w_p n_{2p} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ w_1 n_{m1} & w_2 n_{m2} & \dots & w_n n_{mp} \end{bmatrix} \square \ V_{ij}=\begin{bmatrix} v_{11} & v_{12} & \dots & v_{1p} \\ v_{21} & v_{22} & \dots & v_{2p} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ v_{m1} & v_{m2} & \dots & v_{mp} \end{bmatrix} \quad (4)$$

Adım 4: İdeal ve negatif-ideal çözümlerin belirlenmesi

Burada maksimizasyon amaçlanıyorsa her bir sütuna ait maksimum değerler olan pozitif ideal çözüm değerleri belirlenir. Daha sonra ise yine her bir sütuna ait minimum değerler elde edilerek negatif ideal çözüm değerleri belirlenmiş olur. Eğer amaç minimizasyon ise elde edilen değerler tam tersi olacaktır (Shyjith vd., 2008). Pozitif ideal çözümlere (5) ve negatif ideal çözümlere (6) ilişkin eşitlikler aşağıda gösterilmiştir.

$$A^{*} = \{v_{1,}^{*} v_{2,}^{*} \dots, v_{n}^{*}\} \text{ her bir sütuna ait maksimum değerler,} \quad (5)$$

$$(A^{-}) = \{v_{1,}^{-} v_{2,}^{-} \dots, v_{n}^{-}\} \text{ her bir sütuna ait minimum değerler,} \quad (6)$$

Adım 5: Uzaklık değerlerinin hesaplanması

Her bir alternatifin pozitif ve negatif ideal çözüme olan uzaklıkları Öklid Uzaklık fonksiyonundan yararlanılarak hesaplanır (Monjezi vd., 2010). Uzaklığın hesaplanması ile ilgili formül eşitlik (7)'de verilmiştir.

$$d_{ij} = \sqrt{\sum_{k=1}^{p} (x_{ik} - x_{jk})^{2}} \quad (7)$$

x_{ik} : i. gözlemin k. değişken değeri

x_{jk} : j. gözlemin k. değişken değeri

p: değişken sayısını göstermektedir.

Eşitlik (7)'deki formül genelleştirilerek, pozitif ideal uzaklığın hesaplanmasında eşitlik (8) ve negatif ideal uzaklığın hesaplanmasında eşitlik (9) kullanılır.

$$S_{i}^{*} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{j}^{*})^{2}} \quad (8)$$

$$S_{i}^{-} = \sqrt{\sum_{j=1}^{a} (v_{ij} - v_{j}^{-})^{2}} \quad (9)$$

Burada karar noktası sayısı kadar S_i^{*} ve S_i^{-} olacaktır.

Adım 6: Göreceli yakınlığın elde edilmesi

Her bir karar noktasının ideal çözüme göreceli yakınlığını hesaplanırken pozitif ideal ve negatif ideal uzaklıklardan faydalanılır. İdeal çözüm için göreceli yakınlık C_i^{*} ile gösterilir. Burada C_i^{*} değeri $0 \leq C_i^{*} \leq 1$ aralığında değer alır ve C_i^{*} =1 ilgili karar noktasının pozitif ideal çözüme yakınlaştığını, C_i^{*} =0 ise ilgili karar noktasının negatif ideal çözüme yakınlaştığını gösterir (Monjezi vd., 2010). İdeal çözüme nispi yakınlığın hesaplanmasında eşitlik (10) kullanılır.

$$C_{i}^{*} = \frac{S_{i}^{-}}{S_{i}^{-} + S_{i}^{*}} \quad (10)$$

Adım 7: Sıralama yapılması

Bu adımda göreceli yakınlığa göre bir sıralama yapılır (Monjezi vd., 2010).

3. Bulgular

Bu çalışmada, çevresel sürdürülebilirlik perspektifinden akıllı ulaşım sistemlerinin performanslarını değerlendirmek için TOPSIS yöntemi kullanılmıştır. TOPSIS analizi, her bir alternatifin belirlenen kriterler doğrultusunda performansını değerlendirmek ve sıralamak amacıyla gerçekleştirilmiştir.

İlk adımda, kriterler ve alternatifler için karar matrisi oluşturulmuştur. Bu matris, her bir alternatifin belirlenen kriterler doğrultusunda performansını sayısal olarak ifade etmektedir. Tablo 3, AUS için karar matrisini göstermektedir.

Tablo 3. Karar matrisi

Kriterler	EOS	PESS	OAPS	ABPS
Karbon Emisyonlarının Azaltılması (Ton CO2 /yıl)	2000	1500	1800	2200
Enerji Verimliliği (km/kWh)	5,5	6,0	5,8	6,2
Kaynak Kullanımı (MJ/yıl)	8000	7500	7800	7200
Hava Kalitesine Etki (mikrogram/m^3)	15	12	14	16
Yenilenebilir Enerji Kullanımı (%)	30	25	35	40

İkinci adımda karar matrisindeki değerler, TOPSIS analizi için normalizasyon işlemine tabi tutulmuştur (Tablo 4). Normalizasyon işlemi, kriterler arasındaki farklı birimleri ortadan kaldırarak karşılaştırmayı mümkün kılmaktadır.

Üçüncü adımda normalizasyon matrisindeki değerlere kriter ağırlıkları uygulanarak ağırlıklı normalizasyon matrisi oluşturulmuştur (Tablo 5). Bu matris, kriterlerin önem derecelerini dikkate alarak her bir alternatifin performansını daha doğru bir şekilde değerlendirmektedir.

Tablo 4. Normalizasyon matrisi (N_{ij})

Kriterler	EOS	PESS	OAPS	ABPS
Karbon Emisyonlarının Azaltılması	0,484	0,363	0,436	0,533
Enerji Verimliliği	0,446	0,487	0,471	0,504
Kaynak Kullanımı	0,495	0,464	0,483	0,446
Hava Kalitesine Etki	0,474	0,379	0,442	0,505
Yenilenebilir Enerji Kullanımı	0,421	0,351	0,491	0,562

Tablo 5. Ağırlıklı normalizasyon matrisi (V_{ij})

Kriterler	EOS	PESS	OAPS	ABPS
Karbon Emisyonlarının Azaltılması	0,145	0,109	0,131	0,160
Enerji Verimliliği	0,120	0,131	0,127	0,136
Kaynak Kullanımı	0,074	0,070	0,072	0,067
Hava Kalitesine Etki	0,071	0,057	0,066	0,076
Yenilenebilir Enerji Kullanımı	0,055	0,045	0,064	0,073

Dördüncü adımda TOPSIS yönteminde, pozitif ve negatif ideal çözümler belirlenmiştir. Pozitif ideal çözüm, her bir kriter için en yüksek performans değerlerini, negatif ideal çözüm ise en düşük performans değerlerini ifade etmektedir. Aşağıdaki değerler pozitif ve negatif ideal çözümleri göstermektedir.

Pozitif İdeal Çözüm (A*): {0,160 0,136 0,067 0,076 0,073}

Negatif İdeal Çözüm (A-): {0,109 0,120 0,074 0,057 0,045}

Beşinci adımda her bir alternatifin pozitif ve negatif ideal çözümlere olan uzaklıkları (Tablo 6) hesaplanmıştır.

Tablo 6. Uzaklıkların hesaplanması

Alternatifler	S_i^*	S_i^-
EOS	0,027	0,073
PESS	0,079	0,029
OAPS	0,051	0,049
ABPS	0,046	0,081

Altıncı adımda, her bir alternatifin göreceli yakınlık değerleri hesaplanmıştır (Tablo 7). Göreceli yakınlık değeri, bir alternatifin pozitif ideal çözüme ne kadar yakın olduğunu göstermektedir.

Son adımda ise göreceli yakınlık değerlerine göre sıralama yapılmıştır. TOPSIS analizi sonucunda, alternatifler arasında en yüksek göreceli yakınlık değerine sahip olan EOS en iyi performansı göstermiş olup sıralama şu şekildedir:

1. EOS: 0,730
2. ABPS: 0,637
3. OAPS: 0,490
4. PESS: 0,269

Tablo 7. Göreceli yakınlık (C_i^*)

Alternatifler	C
EOS	0,730
PESS	0,269
OAPS	0,490
ABPS	0,637

EOS, en yüksek göreceli yakınlık değerine sahip olup, karbon emisyonlarının azaltılması, enerji verimliliği, kaynak kullanımı, hava kalitesine etki ve yenilenebilir enerji kullanımı kriterlerinde diğer sistemlere kıyasla daha iyi performans göstermektedir. ABPS, ikinci sırada yer almakta olup, özellikle karbon emisyonlarının azaltılması ve yenilenebilir enerji kullanımı açısından güçlü bir performans sergilemektedir. OAPS ve PESS, sırasıyla üçüncü ve dördüncü sırada yer almakta olup, diğer sistemlere kıyasla daha düşük performans göstermektedir. Bu sistemlerin, enerji verimliliği ve kaynak kullanımı gibi kriterlerde iyileştirmeler yapması gerekmektedir. Bulgular, elektrikli otobüsler ve akıllı bisikletlerin yüksek sürdürülebilirlik performansları ile öne çıktığını gösterirken, otonom araçlar ve elektrikli skuterlerin belirli alanlarda geliştirme potansiyeline sahip olduğunu ortaya koymaktadır.

4. Tartışma ve Sonuç

Bu çalışma, farklı akıllı ulaşım sistemlerinin çevresel sürdürülebilirlik kriterleri açısından değerlendirilmesini amaçlamaktadır. Karbon emisyonlarının azaltılması, enerji verimliliği, kaynak kullanımı, hava kalitesine etki ve yenilenebilir enerji kullanımı kriterleri dikkate alınarak dört farklı akıllı ulaşım sistemi (elektrikli otobüs sistemi, paylaşımlı elektrikli skuter sistemi, otonom araç paylaşım sistemi ve akıllı bisiklet paylaşım sistemi) TOPSIS yöntemi ile analiz edilmiştir.

EOS, çevresel sürdürülebilirlik açısından en iyi seçenek olarak belirlenmiştir (Tablo 7). En yüksek göreceli yakınlık değerine (0,730) sahip olan bu sistem, karbon emisyonlarının azaltılması ve enerji verimliliği konularında üstün performans sergilemektedir (Tablo 5). EOS, fosil yakıt kullanımını azaltarak kaynak kullanımını optimize ederken, hava kalitesine de olumlu katkı sağlamaktadır. Elektrikli otobüslerin karbon emisyonlarının azaltılmasında ve enerji verimliliğinde iyi bir performans gösterdiği, çeşitli çalışmalar tarafından da desteklenmektedir. Du ve Kommalapati (2021), elektrikli otobüslerin sıfır emisyonla çalıştığını ve fosil yakıt kullanımını minimize ederek hava kalitesini iyileştirdiğini belirtmiştir. Dreier ve diğerleri (2018), Mao ve diğerleri (2020) ve Zhou ve diğerleri (2016), çalışmalarında dizel otobüslerden elektrikli otobüslere geçişte emisyon miktarının azaldığını ortaya koymuştur. Bununla birlikte, elektrikli otobüslerin diğer elektrikli araçlar gibi yaşam döngüsü analizinde belirli aşamalarda emisyon tükettiği de göz ardı edilmemelidir. Mao ve diğerleri (2020), yaşam boyu enerji kullanımı ve sera gazı emisyonlarına yönelik yaptığı çalışmasında elektrikli otobüslerin emisyon kaynağının elektrik üretimi (%63,9) ve şarj süreci (%30,9) aşamaları olduğunu bildirmiştir. Ancak, toplu taşıma aracı olarak elektrikli otobüsler, daha fazla yolcu taşıma kapasitesi sebebiyle kişi başına değerler düştüğü için bireysel motorlu taşıtlara kıyasla daha çevre dostu olarak algılanmaktadır. Bu özellikleri, EOS'un diğer sistemler arasında en sürdürülebilir seçenek olduğunu ve bu sistemlerin şehir içi toplu taşımada yaygınlaştırılmasının faydalı olabileceğini göstermektedir. Elektrikli otobüslerin kullanımının yaygınlaştırılması için artık günümüzde hükümetler ve yerel yönetimler tarafından teşvik edici politikalar uygulanmaktadır. Bu teşvikler, finansal destekler, vergi indirimleri ve altyapı yatırımları şeklinde olabilmektedir.

ABPS, ikinci en yüksek göreceli yakınlık değerine (0.637) sahiptir (Tablo 7). ABPS, fosil yakıt kullanmaması ve tamamen yenilenebilir enerji ile çalışması nedeniyle çevresel sürdürülebilirlik açısından güçlü bir alternatif olarak öne çıkmaktadır. Karbon emisyonlarını azaltma ve enerji verimliliği konularında çok etkili olan bu sistem, hava kalitesini iyileştirme konusunda da önemli katkılar sağlamaktadır (Tablo 5). Akıllı bisiklet paylaşım sistemleri de literatürde çevre dostu bir alternatif olarak öne çıkmaktadır (Fan ve Zheng, 2020; Hamilton ve Wichman, 2018; Wang ve Zhou, 2017). Qiu ve He (2018), bisiklet paylaşım sistemlerinin kısa mesafeli yolculuklar için etkili ve ekonomik bir ulaşım sağladığını, böylece karbon emisyonlarını ve enerji tüketimini azaltmada önemli katkılar sunduğunu ifade etmektedir. Bu bağlamda, çalışmanın bulguları ile literatürdeki veriler arasında tutarlılık gözlenmektedir. Bisiklet paylaşım sistemlerinin altyapısının geliştirilmesi ve bireysel ulaşımda çevre dostu bir seçenek olarak desteklenmesi, şehirlerin çevresel sürdürülebilirlik hedeflerine ulaşmasına yardımcı olabilir.

OAPS, üçüncü sırada yer almakta ve ortalama bir performans sergilemektedir (Tablo 7). OAPS, karbon emisyonlarının azaltılması ve enerji verimliliği konularında makul bir performans göstermesine rağmen, kaynak kullanımı ve yenilenebilir enerji kullanımı açısından diğer iki sisteme göre daha az avantajlıdır. Hava kalitesine katkısı ve çevresel sürdürülebilirlik açısından ortalama bir performans sergileyen bu sistem, geliştirilmesi gereken alanlara sahiptir. Otonom araç paylaşım sistemleri konusunda literatür daha karmaşık sonuçlar sunmaktadır. Otonom araçların çevreyi olumlu yönde etkileyecek özerklik derecesine ulaşmayı sağlayacak teknoloji hâlâ geliştirilme aşamasındadır (Society of Automotive Engineers, 2018). Fagnant ve Kockelman (2014), Patella ve diğerleri (2019) ve Wadud ve diğerleri (2016), otonom araçların potansiyel olarak emisyon miktarını azaltabileceğini ve enerji verimliliğini artırabileceğini belirtseler de, enerji verimliliği ve kaynak kullanımı açısından henüz beklenen performansı tam olarak sağlayamadığını vurgulamışlardır. Çalışmada da OAPS'ın diğer sistemlere göre daha düşük performans sergilediği gözlemlenmiş olup (Tablo 5) bu bulgu literatür ile tutarlıdır. Otonom araçların enerji verimliliğini ve çevresel performansını artırmak için teknoloji geliştirme ve yenilikçi çözümler araştırılmalıdır. Bu araçların elektrikli versiyonlarının yaygınlaştırılması, çevresel etkilerini olumlu yönde etkileyecektir.

PESS, en düşük göreceli yakınlık değerine (0.269) sahip olup çevresel sürdürülebilirlik açısından en az avantajlı sistem olarak belirlenmiştir (Tablo 7). PESS, enerji verimliliği ve karbon emisyonlarının azaltılması konularında belirli faydalar sağlasa da, kaynak kullanımı ve hava kalitesine etki konularında yeterince güçlü değildir (Tablo 5). Ayrıca, yenilenebilir enerji kullanımı da diğer sistemlere göre daha düşüktür (Tablo 5). Paylaşımlı elektrikli skuter sistemleri, literatürde hem avantajları hem de dezavantajları ile ele alınmaktadır. Reis ve diğerleri (2023), elektrikli skuterlerin kısa mesafeli yolculuklar için sürdürülebilir bir çözüm sunduğunu ancak bu araçların enerji verimliliği ve uzun ömürlülük açısından bazı zorluklar yaşadığını ifade etmektedir. Birçok çalışma paylaşımlı elektrikli skuterlerin sürüş sırasındaki emisyon miktarlarının sıfıra eşit olmasına rağmen sistemin yaşam döngüsü sürecinde emisyon miktarının arttığı konusunda hemfikirdir (Hollingsworth vd., 2019; Moreau vd., 2020; Severengiz vd., 2020). Hollingsworth ve diğerlerine (2019) göre paylaşımlı e-skuter emisyonlarının ana nedeni, malzeme ve üretim aşamasından (%50) kaynaklanmakta olup bu aşamayı da e-skuterlerin günlük olarak toplanması ve yeniden dağıtılması aşaması (%43) takip etmektedir. Ayrıca yazarlara göre paylaşımlı e-skuterlerin çevresel etkileri en çok paylaşımlı e-skuterin günlük kullanımına, skuter kullanım ömrüne, yeniden dengeleme için kat edilen mesafeye ve araç yakıt verimliliğine duyarlıdır (Hollingsworth vd., 2019). Paylaşımlı elektrikli skuterlerin pilleri geri dönüştürülmez ve doğal olarak bozulursa metan gazı üretmekte ve daha fazla çevresel kirliliğe (su, toprak, hava vb.) neden olmaktadır (Chen vd., 2017). Kısa hizmet ömrü ve çevre kirliliği tehlikeleri nedeniyle, paylaşımlı elektrikli mikromobilite araçları pillerinin geri dönüşümü ve yeniden kullanımı oldukça önemlidir. Kazmaier ve diğerlerine (2020) göre paylaşımlı e-skuterların hizmet ömrünü artırarak sera gazı emisyonları e-skuter başına toplamda %72 oranında azaltılabilmektedir. Çalışmanın bulguları da PESS'in en düşük performansı sergileyerek literatürdeki bu değerlendirmeleri desteklemektedir. Bu sistemlerin performansının artırılması için kullanıcı davranışları üzerinde çalışmalar yapılmalı ve teknolojik iyileştirmeler gerçekleştirilmelidir. Ek olarak, elektrikli skuterlerin batarya ömrü ve verimliliği artırılmalıdır. Daha uzun ömürlü ve çevre dostu bataryaların kullanılması, bu sistemlerin sürdürülebilirliğini artıracaktır.

Bu çalışma, şehir plancıları, ulaşım plancıları, politika yapıcılar, yerel yönetimler ve ilgili muadil tüm aktörler için akıllı ulaşım sistemlerinin çevresel sürdürülebilirlik hedefleri doğrultusunda en uygun seçeneği belirlemede önemli bilgiler sunmaktadır. Akıllı ulaşım sistemlerinin çevresel sürdürülebilirlik performanslarının değerlendirilmesi, sürdürülebilir şehir içi ulaşım politikalarının geliştirilmesine katkıda bulunacaktır. Gelecekteki çalışmalar, bu değerlendirmeleri genişleterek ekonomik ve sosyal sürdürülebilirlik kriterlerini de içermeli ve daha kapsamlı analizler yapılmalıdır. Bu sayede, akıllı ulaşım sistemlerinin tüm yönleriyle değerlendirilmesi mümkün olacaktır.

Etik Kurul Onay Beyanı

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Safety Research Unit

Araştırma Makalesi | Research Article

Caught in the Middle: Examining Pedestrian and Driver Responses to Aggressive Driving

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Abstract

This study investigates the dual roles of individuals as pedestrians and drivers, focusing on their perceptions and attitudes toward aggressive driver behaviors and other traffic-related interactions. By applying Role Theory, the research highlights how societal expectations and role conflicts shape these attitudes, providing a deeper understanding of the psychological and behavioral challenges associated with navigating dual roles. Using a qualitative approach, semi-structured interviews were conducted with 20 participants (10 males and 10 females) to explore their experiences in traffic. Thematic analysis revealed two main themes: Pedestrian Behaviors and Driver Behaviors. Pedestrian behaviors were categorized into Predictable Movement Patterns and Unpredictable Movement Patterns, reflecting the ways pedestrians' actions influence traffic dynamics and safety. Driver behaviors included both positive actions (e.g., Adhering to Rules, Respecting Pedestrian Rights) and negative actions (e.g., Aggressive Driving, Violating Pedestrian Rights). These findings underscore the complexity of pedestrian-driver interactions and emphasize the importance of Role Theory in developing strategies to foster safer and more cooperative traffic environments through targeted educational and policy-based interventions.

Anahtar Kelimeler: *pedestrians, driver anger, anger expression, attitude, road safety, role theory*

Arada Kalmak: Yaya ve Sürücülerin Agresif Sürüşe Tepkilerinin İncelenmesi

Öz

Bu çalışma, bireylerin trafikte hem yaya hem de sürücü olarak üstlendikleri çift rolleri incelemektedir. Bu roller bağlamında agresif sürüş davranışları ve trafikle ilgili diğer etkileşimlere yönelik algı ve tutumlarını araştırmaktadır. Rol Teorisi çerçevesinde, toplumsal beklentilerin ve rol çatışmalarının söz konusu tutumları nasıl şekillendirdiği derinlemesine ele alınmaktadır. Ayrıca, bireylerin bu ikili rol arasında yaşadığı psikolojik ve davranışsal zorluklara dair kapsamlı bir inceleme yapılması amaçlanmıştır. Toplamda 10 kadın ve 10 erkek katılımcıyla gerçekleştirilen görüşmeler aracılığıyla nitel araştırma yöntemi uygulanmıştır. Katılımcıların trafikle ilgili deneyimleri tematik analiz yöntemiyle incelenmiştir. Analiz sonucunda iki ana tema belirlenmiştir: Yaya Davranışları ve Sürücü Davranışları. Yaya davranışları, trafik akışı ve güvenliği etkileyen öngörülebilir ve öngörülemez hareket örüntüleri olmak üzere iki alt kategoriye ayrılmıştır. Sürücü davranışları ise olumlu davranışlar (örneğin, kurallara uyma, yayalara öncelik verme) ve olumsuz davranışlar (örneğin, agresif sürüş, yaya haklarını ihlal etme) şeklinde sınıflandırılmıştır. Elde edilen bulgular, yaya ve sürücü rollerinin dinamiklerini ve etkileşimlerinin karmaşıklığını ortaya koymaktadır. Bu bağlamda sonuçlar, daha güvenli ve iş birliğine dayalı trafik ortamlarının oluşturulmasında Rol Teorisi'nin sağlayabileceği katkılara ve buna yönelik eğitimsel ve politika odaklı müdahalelerin gerekliliğine dikkat çekmektedir.

Keywords: *yayalar, sürücü öfkesi, öfke ifadesi, tutum, yol güvenliği, rol teorisi*

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Caught in the Middle: Examining Pedestrian and Driver Responses to Aggressive Driving

1. Introduction

Traffic environments are complex spaces where individuals frequently assume dual roles: as pedestrians and as drivers. These roles might present contrasting experiences. Pedestrians often navigate traffic with vulnerability. They lack the physical protection offered by vehicles and have limited control over the actions of drivers and surrounding traffic conditions. This leaves them more exposed to risks, especially in high-speed or poorly lit environments. Drivers, on the other hand, benefit from the physical protection of their vehicles and a greater sense of control over their movement. However, this control can sometimes create a false sense of security, potentially reducing their awareness of pedestrians' vulnerability (Hobday & Knight, 2010). Understanding these differing perspectives is essential for fostering empathy and improving safety dynamics between these groups.

This study examines the impact of dual roles on attitudes toward aggressive driver behaviors, with a specific focus on urban environments. Ensuring pedestrian safety, recognized as a critical aspect of global traffic management, is essential for developing safer and more inclusive traffic systems (World Health Organization [WHO], 2023). With pedestrians accounting for a significant proportion of road fatalities, particularly in urban areas, understanding their attitudes toward driver aggression is vital for creating safer and more inclusive traffic environments. Moreover, the interactions between pedestrians and drivers are often shaped by situational and environmental factors, such as traffic density, road infrastructure, and cultural norms. These factors not only influence pedestrian attitudes but also play a crucial role in determining the likelihood of conflicts and near-misses in urban traffic systems (Liu et al., 2022; Saeipour et al., 2023; Sheykhfard & Haghighi, 2018). This study builds on existing research to explore these dynamics, aiming to inform targeted interventions and policy recommendations.

Pedestrians in developing countries face heightened risks due to inadequate infrastructure and limited protective regulations (WHO, 2023). In Turkey, pedestrians account for 23.3% of traffic fatalities, emphasizing their vulnerability (Turkish Statistical Institute [TÜİK], 2023). Based on data from the Turkish Statistical Institute, drivers are identified as the primary cause of accidents (86.8%), with pedestrians as the second main cause (9.5%). However, when the fatality rates among road user groups are examined, pedestrians account for 23.3% of road traffic fatalities (TÜİK, 2023). Combining global and local data provides a nuanced understanding of pedestrian vulnerability, informing strategies tailored to different socioeconomic and infrastructural contexts.

1.1. The Vulnerability of Pedestrians in Traffic Environments

Pedestrians are considered a vulnerable road user group since they do not have protective equipment like vehicles do, making them more susceptible to injuries in the event of a traffic accident. The absence of physical barriers (e.g., airbags), which causes direct exposure to potential hazards, indicates the need for increased attention and safety measures for pedestrians in road safety (WHO, 2023). The risk of being injured in an accident is significantly influenced by the speed of the vehicle; however, this risk is particularly heightened for pedestrians due to their vulnerability (Rosén et al., 2010). These findings highlight the critical importance of understanding factors that contribute to pedestrian vulnerability, particularly in the context of driver behaviors.

Aggressive driver behaviors, such as speeding and failing to yield at crosswalks, exacerbate pedestrians' vulnerability by increasing physical risks and influencing their crossing behaviors (Liu et al., 2022). These interactions often create a heightened sense of vulnerability among pedestrians, leading to stress and fear in traffic environments. For instance, such behaviors significantly influence pedestrians' willingness to engage in safe crossing practices and their overall traffic behavior (Saeipour et al., 2023). This underscores the need to examine driver aggression from a pedestrian's perspective to address these challenges effectively.

1.2. Anger and Its Role in Traffic Interactions

Anger is a fundamental emotion frequently experienced in traffic settings, particularly by drivers, and it plays a critical role in shaping interactions between road users. Aggressive behaviors driven by anger, such as verbal aggression, tailgating, or failing to yield, can escalate into dangerous situations, especially for vulnerable road users like pedestrians (Deffenbacher et al., 2002; Cinnamon et al., 2011).

These behaviors not only create immediate physical risks but also influence pedestrian stress and decision-making in traffic environments. This section examines the emotional and behavioral impacts of anger on pedestrians and highlights the dynamics of dual roles in traffic interactions.

1.2.1. Aggressive Driver Behaviors.

Aggressive driving behaviors, such as failing to yield or speeding near crosswalks, significantly contribute to pedestrian fatalities and stress (Cinnamon et al., 2011). These behaviors create immediate risks and influence pedestrian decision-making under stress, such as hesitation to cross roads or engaging in risky maneuvers. Deffenbacher et al. (2002) categorized anger expression into four distinct types, each with unique implications for pedestrian safety. Verbal aggressive expression, such as shouting, cursing, or honking, heightens pedestrians’ stress and fear. Physical aggressive expression, which involves gestures or throwing objects, further escalates traffic tensions. Vehicle-related aggression, including tailgating, reckless driving, or speeding, directly endangers pedestrians' physical safety (Cinnamon et al., 2011). In contrast, constructive expressions of anger involve redirecting anger into calming strategies, such as deep breathing or adapting driving behaviors to minimize harm.

Understanding these types provides critical insights into how aggression manifests in traffic and impacts pedestrian well-being. For example, verbal aggression can cause immediate psychological distress, while vehicle-related aggression might lead to avoidance behaviors or long-term anxiety. Effective interventions must address these diverse manifestations to reduce the risks associated with driver anger.

1.2.2. Pedestrian Responses to Aggressive Driver Behaviors: Perceptions and Emotional Impacts.

Pedestrians frequently experience stress, fear, and frustration as a result of aggressive driver behaviors. These behaviors create immediate risks and influence pedestrian decision-making under stress, such as hesitation to cross roads or engaging in risky maneuvers (Cinnamon et al., 2011; Liu et al., 2022). High traffic densities often exacerbate this effect, as pedestrians perceive safety in numbers and assume that drivers are more likely to yield to groups rather than individuals, leading to group-based risk-taking behaviors (Liu et al., 2022; Salamati et al., 2013). The absence of protective barriers makes pedestrians particularly vulnerable, amplifying their emotional and psychological reactions to driver aggression (WHO, 2023). While marked crosswalks can provide pedestrians with a sense of security, they may also create a false sense of safety, causing pedestrians to take riskier crossing decisions (Pfortmueller et al., 2014). Furthermore, infrastructural factors such as poorly designed crossings or absence of traffic calming measures may lead to heightened pedestrian stress and avoidance behaviors (Schroeder & Rouphail, 2011; Sheykhfard et al., 2022).

Cultural factors also influence pedestrian responses to aggressive driver behavior. In certain cultural contexts, pedestrians may adopt confrontational strategies when threatened, whereas in others, they exhibit avoidance behaviors to minimize risk and conflict (Sheykhfard & Haghighi, 2018). Examining these diverse responses highlights the need for context-specific interventions, such as targeted infrastructure improvements and educational campaigns, to mitigate pedestrian stress and promote safer traffic interactions. Understanding these diverse influences—ranging from psychological stress and group behaviors to cultural norms and infrastructure—provides a holistic framework for addressing pedestrian safety in shared road environments (Cloutier et al., 2017; Sheykhfard et al., 2022; Schroeder & Rouphail, 2011).

1.3. Dual Role of Road Users

Attitudes are key precursors to anger-related behaviors in traffic contexts (Ambak et al., 2017; Youssef et al., 2023). Negative attitudes among pedestrians toward other road users are linked to higher rates of aggressive violations and transgressions, as well as reduced attentiveness (Serin et al., 2018). Similarly, drivers' negative attitudes toward pedestrians contribute to escalating conflicts and decreased mutual trust, perpetuating a cycle of aggression (Febres et al., 2021; Serin et al., 2018). Although driver behaviors are the primary cause of road traffic accidents, pedestrians also play a crucial role in road safety outcomes (WHO, 2023).

Research on pedestrian behaviors has focused primarily on specific contexts, such as unsignalized and signalized crosswalks (Ren et al., 2011; Yang et al., 2022), and the impact of distractions like mobile phone use (Schwebel et al., 2012; Zhou et al., 2019). These behaviors increase accident risks, particularly for pedestrians, whose vulnerability amplifies the severity of injuries compared to drivers (Rosén et al., 2010; Zhou et al., 2019). However, exploration of pedestrians' perceptions of drivers' undesirable behaviors remains limited (Nordfjærn et al., 2011). Individuals alternating between pedestrian and driver roles provide valuable insights into these interactions, offering a nuanced perspective on both pedestrian vulnerabilities and driver behaviors (Gibson et al., 2018).

Role Theory offers a foundational framework for understanding how individuals navigate multiple social roles. It posits that people adopt specific behaviors, attitudes, and responsibilities based on the roles they occupy, with each role governed by societal expectations, norms, and responsibilities (Stryker & Burke, 2000). For dual-role road users, alternating between pedestrian and driver roles can lead to significant tension, as the behavioral expectations and responsibilities of these roles often conflict (Nordfjærn et al., 2011). This theoretical lens provides a valuable basis for analyzing the psychological and behavioral challenges faced by individuals managing these dual roles in traffic contexts.

Previous research suggests that pedestrians often perceive drivers' behaviors as threatening and unpredictable, which can contribute to heightened risk perceptions and defensive actions in traffic environments (Nordfjærn et al., 2011; Serin et al., 2018). Conversely, drivers often express frustration with pedestrians' perceived inattentiveness, which they interpret as violations of shared traffic norms (Febres et al., 2021; Nordfjærn et al., 2011).

Role Theory highlights how these mutual frustrations stem from conflicting role expectations: pedestrians expect protection and caution from drivers, while drivers expect attentiveness and compliance with traffic norms from pedestrians (Febres et al., 2021; Nordfjærn et al., 2011). This reciprocal nature of frustrations underscores the need to address role-related dynamics in traffic safety strategies. By applying Role Theory, the study emphasizes the importance of fostering mutual empathy and awareness between road users. Educational interventions, such as driver-pedestrian awareness campaigns or virtual reality simulations, can promote shared responsibilities, mitigate role-related tensions, and create safer, more cooperative traffic environments (Nigam et al., 2021; Schuring et al., 2023).

1.4. Research Gap and Aim of the Study

This study addresses a critical and underexplored gap in traffic safety research: the dual perspectives of individuals who alternate between being pedestrians and drivers. While prior studies have treated pedestrians and drivers as distinct entities, few have examined how these dual roles interact to shape attitudes toward aggressive driving behaviors and road safety outcomes. This research is the first of its kind to integrate Role Theory as a framework for understanding how societal expectations, role conflicts, and role perceptions influence individuals' behaviors and attitudes in shared traffic environments.

By revealing the dynamic tensions between pedestrians' sense of vulnerability and drivers' perceived control, this study provides novel insights into the psychological and behavioral contradictions inherent in these roles. For example, individuals may empathize with drivers' frustrations when navigating traffic but simultaneously demand heightened caution and protection as pedestrians. The findings not only advance current understanding of road user interactions but also offer a foundation for targeted interventions, such as educational programs and policies, aimed at fostering mutual empathy, reducing role-related conflicts, and promoting safer, more cooperative traffic environments.

2. Method

2.1. Participants

The study included 20 participants (10 males, 10 females) aged between 18 and 43 years (*M* = 23.8, *SD* = 5.27). Female participants reported an average age of 24 years (*SD* = 6.60), whereas the average age for male participants was 23 years (*SD* = 3.80). All participants held a valid driving license, a deliberate criterion to ensure that they could reflect on their experiences from both perspectives: as pedestrians and as drivers. Participants' daily pedestrian activity durations varied across genders, as summarized in Table 1. On average, participants spent 86.25 minutes daily (*SD* = 61.28) navigating traffic as pedestrians. Female participants reported slightly longer durations (*M* = 90, *SD* = 78.31) compared to males (*M* = 82.5, *SD* = 41.98).

As shown in Figure 1, time categories for pedestrian activities revealed notable gender-based differences. Women most frequently reported walking during "Morning Only" and displayed greater variability, as evidenced by their responses in the "It depends" category. In contrast, men reported more structured patterns, predominantly walking during "Noon Only" and "Afternoon Only". Combined categories, such as "Morning + Afternoon" and "Afternoon + Evening", showed similar participation across both genders.

Table 1. Characteristics of participants

ID	Age	Gender	Minutes spent as pedestrian	Time Category	Interview method
1	21	Woman	20	Morning, Noon, Afternoon, Evening	Face to face
2	22	Man	90	Morning, Afternoon	Online
3	22	Man	90	Night	Face to face
4	21	Woman	30	Noon	Face to face
5	23	Woman	180	It depends*	Face to face
6	22	Woman	60	Morning, Evening	Face to face
7	22	Woman	20	Morning	Face to face
8	22	Man	30	Noon, Afternoon, Evening	Face to face
9	22	Woman	180	Morning, Evening	Face to face
10	21	Man	120	Morning	Online
11	18	Man	120	Noon	Online
12	21	Man	15	Afternoon, Evening	Face to face
13	22	Man	120	Noon, Evening	Online
14	30	Man	120	Morning	Face to face
15	29	Man	90	It depends*	Online
16	26	Man	30	Noon, Afternoon	Online
17	23	Woman	30	Noon, Afternoon, Night	Online
18	24	Woman	180	It depends*	Online
19	43	Woman	20	It depends*	Online
20	23	Woman	180	Morning, Afternoon, Evening	Face to face

*The participant's responses did not indicate specific time intervals, suggesting that their time spent as a pedestrian in traffic varies.

The sample size of 20 participants was chosen based on achieving data saturation, ensuring a thorough exploration of recurring themes while maintaining diversity in participant responses. Previous research supports the sufficiency of small, homogenous samples in qualitative studies, particularly when participants share common characteristics (Young & Casey, 2018; Vasileiou et al., 2018). In this study, the dual roles of participants as pedestrians and drivers provided a focused yet diverse sample, facilitating rich, in-depth insights into their traffic experiences.

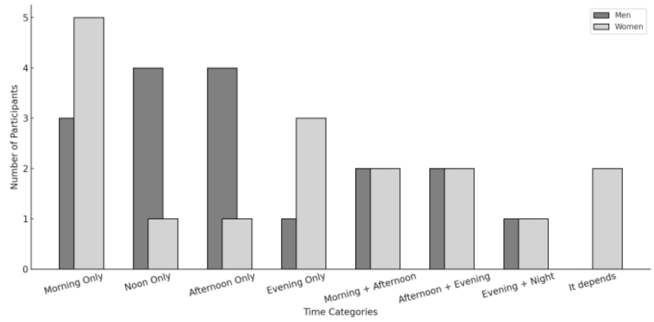

Figure 1. Gender-Wise Distribution of Participants Across Time Categories.

2.2. Instruments

Data were collected using a demographic information form and semi-structured interviews. The demographic form included questions on participants' age, gender, and time spent navigating traffic as pedestrians and drivers. The interview guide consisted of 15 open-ended questions, which were developed and adapted from well-established scales to ensure reliability and relevance to the research objectives. Specifically, questions were drawn from the Driver Anger Scale (Deffenbacher et al., 2002), which explores participants' emotional responses to traffic interactions, the Driver Behavior Questionnaire (Reason et al., 1990), designed to identify patterns of risky and aggressive driving behaviors, and the Pedestrian Behavior Questionnaire (Serin et al., 2018), which focuses on pedestrian behaviors, particularly in shared traffic environments.

The semi-structured format allowed participants to provide detailed responses about their perceptions, emotions, and experiences as both pedestrians and drivers, encouraging them to reflect on their dual roles. Prior to the main data collection phase, pilot testing was conducted to ensure that the questions were clear, relevant, and aligned with the study's objectives. Based on the feedback from the pilot phase, minor refinements were made to improve the clarity and flow of the interview guide. The full list of questions is as follows: 1) What is your perspective on aggressive driver behaviors as pedestrians?; 2) What situations in traffic cause you stress as a pedestrian?; 3) How do you cope with stressful situations in traffic as a pedestrian?; 4) What driver behaviors make you angry as a pedestrian?; 5) What aggressive driver behaviors have you encountered as a pedestrian?; 6) What driver behaviors make you feel comfortable when you are in traffic as a pedestrian?; 7) What aggressive driver behaviors do you exhibit towards pedestrians when you are a driver?; 8) How do the difficulties you face in traffic as a pedestrian affect your daily life outside of traffic?; 9) In your opinion, what driver behaviors would make your life easier in traffic as a pedestrian?; 10) How do you think aggressive drivers can manage their anger in traffic?; 11) Do you observe any changes in your behavior as a pedestrian in situations where you are angry in traffic?; 12) How do you control your behavior as a pedestrian when you are angry in traffic?; 13) What kind of influence do you think you have on driver behavior as a pedestrian in traffic?; 14) Do you think you exhibit behaviors as a pedestrian in traffic that provoke drivers' anger?; 15) Which pedestrian behaviors do you think can anger drivers in traffic?

2.3. Procedure

Ethical approval for the research was obtained from the TOBB ETU Human Research Ethics Committee. Snowball sampling was used to recruit participants, focusing on individuals with regular pedestrian activity in traffic. Individual interviews were conducted in quiet settings, either in-person or online, depending on participants' preferences. Each interview lasted an average of 30–40 minutes and was conducted solely by the first author. Audio recordings were obtained from participants who provided consent, while detailed notes were taken during interviews with those who did not agree to be recorded. Participants were informed about the study and provided consent by completing the consent form.

2.4. Data Analysis

The interview data were analyzed using thematic analysis, following Braun and Clarke's (2006) six-phase framework. The process involved familiarization with the data, initial coding, theme identification, and iterative refinement. Transcripts were carefully reviewed, and initial codes were generated inductively to capture recurring patterns. These codes were subsequently organized into overarching themes and subthemes, which were refined to ensure internal consistency and coherence. To enhance the reliability of the analysis, coding discrepancies were addressed through collaborative discussions among the research team until consensus was reached. Rather than focusing on statistical measures such as inter-rater reliability, a reflexive and dialogic approach was employed to ensure credibility of the analysis. A semantic-level strategy guided the analysis, prioritizing participants' explicit narratives and avoiding interpretive assumptions. The resulting themes captured the emotional and behavioral dynamics of participants' dual roles, highlighting their unique experiences as both pedestrians and drivers.

3. Results

This section presents the results of the thematic analysis, highlighting the behavioral and emotional dynamics of participants in their dual roles as pedestrians and drivers. Two primary themes, 'Pedestrian Behaviors' and 'Driver Behaviors,' were identified, each encompassing multiple subthemes and categories that reflect the complexities of traffic interactions. Table 2 provides a comprehensive overview of the themes, subthemes, and categories that emerged from the analysis.

3.1. Pedestrian Behaviors

This theme captures the participants' reflections on their own behaviors as pedestrians, highlighting actions that either align with or deviate from traffic safety norms. Two subthemes were identified: "Safety-Conscious Pedestrian Behaviors" and "Behavioral Risks in Pedestrians."

3.1.1. Safety-Conscious Pedestrian Behaviors

Participants emphasized the importance of adopting safe behaviors as pedestrians, which contribute to their own safety as well as overall traffic safety. These behaviors were grouped into two categories:

3.1.1.1. Adhering to Traffic Signals.

Participants described following traffic lights and waiting for the green pedestrian signal as critical behaviors that minimize risks for both pedestrians and drivers. Such compliance ensures predictable traffic patterns and fosters mutual respect on the road. These behaviors were not only perceived as essential for personal safety but also as a form of accountability in shared spaces.

"Pedestrians who do not suddenly dart into traffic while paying attention to traffic lights." (P3, M, 22)

"These days, there are so many pedestrians, especially young people, who use headphones or look at their phones. I can't count how many times I've avoided the risk of an accident because they don't hear the sound of the horn or assume they have the right to step onto the road just because they're pedestrians." (P14, M, 30)

Table 2. Themes, subthemes and categories

Theme	Subtheme	Category
Pedestrian Behaviors	Safety-Conscious Pedestrian Behaviors	Adhering to Traffic Signals
		Optimal Use of Infrastructure
	Behavioral Risks in Pedestrians	Disregard for Traffic Rules
		Unpredictable Movement Patterns
Driver Behaviors	Driver Awareness and Consideration	Compliance with Safety Norms Demonstrating Respect for Pedestrians Pedestrian-Centered Driving
	Driver Aggression and Rule Violations	Expressions of Frustration
		Neglecting Pedestrian Rights
		General Rule-Breaking

3.1.1.2. Optimal Use of Infrastructure.

Proper use of pedestrian-specific infrastructure, such as sidewalks and crosswalks, was highlighted as a key practice for maintaining safety. Participants emphasized that avoiding abrupt movements into traffic, crossing streets while observing traffic signals, walking at a moderate pace, and utilizing sidewalks significantly reduce conflicts with vehicles. These actions also demonstrate awareness of shared road responsibilities, helping to create a more orderly traffic environment.

"The improper use of sidewalks designed for people with disabilities by pedestrians can also cause various problems. Additionally, the government's failure to address damaged sidewalks or delayed interventions also leads to issues." (P4, F, 21)

While safety-conscious pedestrian behaviors contribute to reducing conflicts and fostering mutual respect in traffic, participants also highlighted the prevalence of risky behaviors that undermine these positive outcomes and escalate tensions between pedestrians and drivers.

3.1.2. Behavioral Risks in Pedestrians

Risky pedestrian behaviors were identified as those that increase the likelihood of accidents or provoke aggressive reactions from drivers. These were further divided into two categories:

3.1.2.1. Disregard for Traffic Rules.

Participants frequently noted that behaviors such as ignoring red lights, jaywalking, or crossing streets in undesignated areas lead to unsafe situations. Such actions not only put pedestrians at risk but also frustrate drivers, potentially escalating aggressive driving behaviors. The lack of rule adherence was perceived as a major contributor to traffic tensions.

"Pedestrians who fail to heed traffic lights, suddenly dart into traffic, and violate the rules." (P17, F, 23)

"Implementing necessary sanctions for pedestrians as much as for drivers regarding the disregard of traffic rules could be a solution to prevent conflicts. In my opinion, pedestrians are not subjected to sufficient sanctions; at least, this is what I can say based on my own experiences." (P20, F, 23)

3.1.2.2. Unpredictable Movement Patterns.

Sudden and erratic pedestrian movements, such as stepping into traffic without looking or abruptly changing direction, were identified as significant safety risks. Participants pointed out that these actions often catch drivers off guard, leaving little time to react appropriately. Such behaviors were frequently linked to increased accidents and heightened driver frustration.

"Making sudden or unpredictable movements." (P5, F, 23)

"Both pedestrians and drivers being distracted by their phones in traffic often leads to sudden movements. For instance, when I was driving, there was a time when someone didn't see me on the road because they were looking at their phone, which caused me to suddenly swerve left and almost have an

accident. That's why I think this is a very risky behavior." (P7, F, 22)

While risky pedestrian behaviors increase the likelihood of accidents, participants emphasized that driver behaviors, including both positive and negative actions, play an equally critical role in shaping traffic dynamics.

3.2. Driver Behaviors

This theme focuces on participants' perceptions of driver behaviors that either facilitate or hinder pedestrian safety. Two subthemes were identified: "Driver Awareness and Consideration" and "Driver Aggression and Rule Violations."

3.2.1. Driver Awareness and Consideration

Participants highlighted positive driver behaviors that supported pedestrian safety, categorized as follows:

3.2.1.1. Compliance with Safety Norms.

Adhering to speed limits, yielding to pedestrians at crosswalks, and respecting pedestrian signals were frequently mentioned as crucial behaviors. These actions were praised for reducing traffic conflicts and enhancing mutual trust between pedestrians and drivers. Participants appreciated drivers who consistently followed these rules, viewing them as key contributors to safer road environments.

"Drivers who obey traffic rules, do not violate pedestrian rights, are respectful, and can empathize." (P12, M, 21)

"Honestly, seeing people shouting and yelling in traffic makes me lose the desire to use public transportation, so I usually try to use the subway. Being in traffic completely stresses me out." (P1, F, 21)

3.2.1.2. Demonstrating Respect for Pedestrians.

Beyond rule compliance, participants valued behaviors that showed genuine consideration for pedestrians, such as slowing down near crosswalks or signaling to pedestrians with hand gestures. Such actions were perceived as respectful and indicative of a driver's empathy and awareness of pedestrian needs.

"Gentle hand and head gestures towards pedestrians were the most appreciated driver behaviors." (P20, F, 23)

"Sometimes there are pedestrians wearing headphones, so they obviously don't hear the horn, and I gesture with my hand. Usually, they nod apologetically. Honestly, I use this gesture too because I liked it when drivers did the same for me when I was a pedestrian." (P16, M, 26)

3.2.1.3. Pedestrian-Centered Driving.

Drivers who actively adapt their behaviors to prioritize pedestrian safety were highlighted as role models. Participants viewed these drivers as thoughtful and considerate, often citing their ability to empathize with the pedestrian perspective. This approach was seen as critical in fostering a cooperative traffic environment.

"I sometimes remember situations when I myself was a pedestrian, and that's why I try to approach pedestrians with more understanding." (P1, F, 21)

"I usually drive, but I didn't have a car when I was a student. So, when I see students or young people walking, I remember my own youth and the challenges I faced on the roads, and I always give way to them. Sometimes, I even help hitchhikers and give them a ride to where they're going." (P19, F, 43)

Although participants appreciated drivers who demonstrated awareness and consideration for pedestrian safety, they also frequently cited aggressive and rule-violating behaviors that undermine these positive interactions and escalate risks for pedestrians.

3.2.2. Driver Aggression and Rule Violations

Participants frequently cited aggressive or careless driver behaviors. These were categorized as follows:

3.2.2.1. Expressions of Frustration.

Behaviors such as honking excessively, shouting, or making offensive gestures were identified as common expressions of driver anger. Participants noted that these actions created stress and discomfort, undermining the sense of safety for pedestrians.

"Drivers who disregard traffic rules, ignore pedestrians, and drive aggressively." (P7, F, 22)

"I believe there is significantly more prejudice and norms directed at women in traffic, whether they are drivers or pedestrians, and I can say this clearly based on my own experiences. I can say that I get yelled at more often when they see that I am a woman." (P9, F, 22)

While expressions of frustration by drivers contribute to an environment of stress and discomfort for pedestrians, neglecting pedestrian rights further exacerbates these tensions, reflecting a broader disregard for road safety norms.

3.2.2.2. Neglecting Pedestrian Rights.

Examples included failing to yield at crosswalks, speeding in rainy conditions, or splashing pedestrians with water. Such actions were described as inconsiderate and indicative of a disregard for pedestrian safety.

"Drivers who speed in rainy weather and splash water on pedestrians show no consideration for others." (P5, F, 23)

"I think drivers feel like being inside a car, like having something protective around them, gives them the right to treat pedestrians badly or ignore them. For example, I don't think people riding motorcycles do the same or even can. Why? Because they don't have anything to protect them from outside contact!" (P14, M, 30)

3.2.2.3. General Rule-Breaking.

Ignoring traffic signs, failing to use turn signals, or excessive speeding were frequently mentioned as hazardous driver behaviors. Participants described these actions as both frustrating and dangerous, emphasizing the uncertainty they created for pedestrians.

"It stresses me out when drivers fail to use turn signals, as I can't predict their next move." (P3, M, 22)

"I definitely think the reason for not following these rules is the lack of enforcement. I know many people who don't follow the rules, saying things like 'no one's watching anyway' or 'nothing will happen to me.' Especially late at night, they don't even pay attention to traffic lights or anything." (P15, M, 29)

These findings provide valuable insights into the behavioral and emotional dynamics of pedestrian-driver interactions, emphasizing the need for targeted interventions to address role conflicts and foster mutual respect in shared traffic environments.

4. Discussion

This study provides critical insights into the interplay between pedestrian vulnerability and driver aggression, highlighting the complex dynamics shaped by individuals' dual roles in traffic. The findings emphasize the significant impact of both pedestrian and driver behaviors on road safety. Participants identified a range of safe and risky behaviors among pedestrians, as well as positive and negative behaviors among drivers, underscoring the reciprocal nature of traffic interactions. The findings from this study offer a nuanced understanding of the interplay between pedestrian vulnerability and driver aggression, which are further explored through the lens of Role Theory.

Role Theory provides a valuable framework for analyzing the societal and situational expectations that govern individual behaviors in traffic contexts. The tension observed in participants' dual roles as pedestrians and drivers reflects the core premise of Role Theory—societal expectations often conflict with situational demands. For instance, pedestrians perceive themselves as vulnerable and deserving of caution from drivers, while drivers often assert authority and control, sometimes at the expense of pedestrian safety. This dichotomy, shaped by role perceptions and societal norms, underscores the complexities of traffic interactions.

Anger emerged as a key emotional factor influencing driver behaviors, often expressed through verbal aggression and the use of vehicles to intimidate. Conversely, pedestrians predominantly reported experiencing stress, employing various coping strategies such as listening to music, practicing breathing exercises, and cognitive reappraisal. These differing emotional responses reflect the inherent power dynamics in traffic, where drivers may feel more empowered to express anger while pedestrians navigate their vulnerability. These findings align with cultural insights from prior studies, suggesting that societal norms and infrastructural challenges exacerbate these emotional disparities (Pradhan & Bhattacharya, 2020; Feng et al., 2020).

The dual-role perspective revealed internal conflicts in attitudes and behaviors, with individuals sometimes justifying aggressive driving actions while expecting caution and respect as pedestrians. This tension illustrates the bidirectional nature of traffic dynamics and the need for targeted interventions that address these contradictions. For example, educational programs that emphasize empathy-building and mutual responsibility could bridge the gap between these conflicting roles, fostering a safer traffic environment. Additionally, considering cultural and contextual factors, such as the prioritization of pedestrian rights in certain societies (Ma et al., 2023; Royko, 2024), can enhance the design of policies and awareness campaigns aimed at reducing aggressive behaviors.

4.1. Dual Roles of Pedestrians and Drivers: Insights Through the Lens of Role Theory

Role Theory provides a critical lens for understanding the complex dynamics of pedestrian and driver interactions, particularly in dual-role users. The results highlight significant role conflicts, shaped by societal expectations and role perceptions, as individuals navigate between these roles. For example, participants reported adherence to traffic rules and demonstrating safety-conscious behaviors as pedestrians, but often justified aggressive driving actions under the pretext of maintaining traffic efficiency. This aligns with the concept of role conflict, where expectations tied to one role (e.g., pedestrian vulnerability) clash with those of another (e.g., driver control and efficiency) (Khan et al., 2014; Nordfjærn et al., 2011; Ma et al., 2023).

Role expectancy, or societal assumptions about appropriate behaviors, further influences these interactions. As pedestrians, participants emphasized the need for drivers to prioritize their safety, reflecting broader societal norms of pedestrian rights. Conversely, as drivers, participants justified behaviors like honking or tailgating, often attributing them to situational demands, such as time constraints or dense traffic conditions. These findings underscore the tension between societal norms and individual behaviors, which is central to Role Theory's premise that social roles are governed by both expectations and situational realities (Nordfjærn et al., 2011; Ma et al., 2023).

Role perception, the way individuals internalize their responsibilities within each role, also emerged as a key theme. Dual-role users often perceived themselves as entitled to protection and caution from drivers as pedestrians, yet felt empowered to assert control as drivers. For instance, participants admitted to expressing frustration at jaywalking pedestrians when driving, despite recognizing their own tendency to cross streets unpredictably as pedestrians. These dual perspectives highlight the fluidity of role perception and its influence on both attitudes and behaviors in traffic contexts (Gibson et al., 2018; Persoskie et al., 2019).

By applying Role Theory, this study provides deeper insights into how dual-role users navigate the conflicting demands of vulnerability and control in traffic environments. The findings emphasize that role conflicts are not just individual struggles but also reflective of broader cultural and structural contexts, such as societal attitudes toward traffic norms and the design of urban infrastructure (Feng et al., 2020; Ma et al., 2023). Addressing these dynamics through educational interventions that emphasize empathy-building and mutual responsibility can foster safer and more cooperative traffic interactions. Additionally, targeted policy measures, such as enhanced pedestrian infrastructure, stricter enforcement of traffic laws, and culturally sensitive public awareness campaigns, can help align societal expectations with individual behaviors. These findings underscore the importance of fostering empathy between road users by encouraging reflection on their behaviors from both roles. Educational campaigns that address role conflicts and promote mutual understanding are essential for mitigating tensions and improving traffic dynamics.

4.2. Expressions of Anger in Traffic Contexts

Anger is a dominant emotion in traffic, often shaping interactions between drivers and pedestrians. Participants in this study identified verbal aggression, such as shouting and using offensive language, as well as physical aggression, including honking excessively or making threatening gestures. These behaviors align with Deffenbacher et al.'s (2002) framework for categorizing anger expressions, which include verbal aggression, physical aggression, vehicle use, and adaptive expressions. Tailgating and sudden braking were commonly mentioned as examples of using vehicles as tools for intimidation, highlighting the physical embodiment of anger in traffic contexts (Holman & Popușoi, 2018).

The situational factors influencing anger expressions were evident, with congestion, delays, and perceived violations of road norms frequently cited as triggers. Previous studies, such as those by Feng et al. (2020) and Pradhan and Bhattacharya (2020), support these findings, demonstrating how environmental stressors in traffic amplify frustration and lead to aggressive behaviors. Participants also noted the normalization of certain aggressive behaviors, such as honking, which is often seen as an acceptable means of communication in Turkish traffic culture (Ersan et al., 2020).

Despite the prevalence of aggression, some participants demonstrated awareness of their anger and employed adaptive coping strategies, such as cognitive reappraisal or taking deep breaths. These findings align with Thompson et al.'s (2012) work on the effectiveness of adaptive coping mechanisms in reducing stress and anger in traffic environments. Educational interventions focusing on anger management and emotional regulation, particularly for professional drivers who spend extended hours in high-stress traffic conditions, are essential to mitigating these behaviors (Shehab & Alkandari, 2021; Kalašová, 2022).

The patterns of anger expression observed in this study underscore the necessity of addressing both individual and systemic factors. Incorporating anger management training into driver education programs and promoting public awareness campaigns that challenge cultural norms around aggression could foster more harmonious interactions on the road. This dual approach—targeting both personal behaviors and societal attitudes—has the potential to significantly improve road safety.

4.3. Cultural and Contextual Insights

Cultural and contextual factors significantly shape traffic behaviors, particularly in societies like Turkey, where unique infrastructural and societal challenges converge. Participants frequently noted the normalization of aggressive driving behaviors, such as honking and speeding, reflecting broader cultural norms that tolerate such actions. This is consistent with findings by Şimşekoğlu (2015) and Ersan et al. (2019), who emphasize the role of societal attitudes in shaping traffic dynamics.

Infrastructure plays a critical role in shaping pedestrian-driver interactions. Participants highlighted issues such as poorly marked crosswalks, limited pedestrian bridges, and narrow sidewalks as contributors to conflict-prone scenarios. Ersan et al. (2020) found that infrastructural improvements, including dedicated pedestrian zones and clearer road markings, significantly reduce tensions and foster safer traffic environments. Moreover, limited enforcement of traffic laws exacerbates these challenges, as drivers may feel emboldened to disregard pedestrian rights, particularly in urban areas with high traffic density (Holman & Popușoi, 2018; Ma et al., 2023).

The cultural context also influences perceptions of hierarchy in traffic. Participants described a tendency for drivers of larger or more expensive vehicles to exhibit dominance, often ignoring traffic regulations at the expense of pedestrians. Such behaviors highlight the need for educational campaigns that promote equality and mutual respect among all road users (Royko, 2024). Studies have shown that culturally tailored interventions, such as public awareness campaigns emphasizing positive driver behaviors, can effectively reduce aggressive driving tendencies (Feng et al., 2020; Duperrex et al., 2002).

Situational factors, such as weather conditions and traffic density, further exacerbate these challenges. Participants frequently cited slippery roads and high-speed traffic as barriers to positive driver behaviors, aligning with findings by Chu (2024) on the impact of environmental factors on traffic dynamics. Similarly, Pradhan and Bhattacharya (2020) emphasize the importance of considering situational realities in the design of traffic interventions and policies.

These findings highlight the interplay between cultural norms, infrastructural realities, and situational factors in shaping traffic behaviors. By addressing these dimensions through culturally sensitive interventions, including educational programs, policy reforms, and infrastructural upgrades, it is possible to foster a safer and more cooperative traffic environment.

4.4. Stress and Coping Mechanisms in Traffic

Traffic environments are inherently dynamic and often pose significant stress, particularly for vulnerable road users such as pedestrians. This study identified driver behaviors, including excessive honking, vehicles speeding too close to pedestrians, and verbal confrontations, as prominent stressors. In line with prior research, environmental factors such as poor visibility (Stoker et al., 2015) and inadequate pedestrian infrastructure (Ersan et al., 2019) further compounded these challenges, creating a heightened sense of vulnerability in urban traffic settings.

Participants described various coping mechanisms employed to manage these stressors. Common strategies included listening to relaxing music, practicing breathing exercises, and reframing stressful situations using cognitive reappraisal. These adaptive methods align with findings that cognitive strategies can effectively mitigate stress in dynamic environments (Gross & John, 2003; Jo et al., 2019). However, certain coping strategies, such as using music to reduce stress, carry potential risks, as prior research has shown their tendency to distract pedestrians from traffic dynamics (Thoma et al., 2013; Thompson et al., 2012).

The dual roles of participants as both pedestrians and drivers also influenced their stress management approaches. As pedestrians, participants often adopted avoidance behaviors, such as stepping back from crosswalks or avoiding eye contact with aggressive drivers, reflecting findings in studies on defensive pedestrian behaviors (Pradhan & Bhattacharya, 2020). As drivers, they reflected on their own pedestrian experiences, fostering empathy and encouraging more considerate driving practices. This interplay underscores the reciprocal nature of pedestrian-driver interactions, where experiences in one role inform behaviors in the other (Ma et al., 2023).

Addressing stress in traffic contexts requires a dual approach. Educational initiatives should emphasize adaptive stress management techniques for both pedestrians and drivers, fostering mutual understanding and resilience. These findings support the value of culturally tailored interventions, as highlighted in Ersan et al. (2020), to address local traffic dynamics effectively. Simultaneously, infrastructure improvements, such as enhanced lighting and pedestrian-friendly urban designs, are essential for reducing external stressors. By integrating these strategies, traffic systems can become safer and more accommodating for all road users (Feng et al., 2020).

4.5. Vulnerability and Power Dynamics in Traffic

The study highlights the contrasting emotional responses of drivers and pedestrians, with anger being predominantly expressed by drivers and stress by pedestrians. This emotional divergence appears to reflect the inherent power dynamics in traffic. Drivers, protected by the physical shielding of their vehicles, often feel a sense of empowerment, which may embolden them to express anger through verbal aggression, honking, or intimidating maneuvers. In contrast, pedestrians, acutely aware of their physical vulnerability, frequently adopt passive or evasive responses to driver aggression. These findings align with previous research emphasizing the vulnerability of pedestrians in shared traffic environments (Ersan et al., 2019; Stoker et al., 2015).

The study's participants described their heightened awareness of these dynamics during their roles as pedestrians, noting how driver behaviors, such as speeding or failing to yield, intensified their sense of insecurity. Similarly, as drivers, participants recognized their capacity to influence pedestrian behavior through actions that either increased or alleviated stress. This dual perspective underscores the importance of addressing these power imbalances to foster safer and more empathetic traffic interactions (Feng et al., 2020).

Despite technological advancements, such as automated vehicles and intelligent transport systems (ITS), the human factor remains critical in traffic safety. Participants noted that while technology can reduce some risks, it cannot substitute the mutual understanding and cooperative behaviors essential for managing complex traffic scenarios. Studies suggest that technology should be seen as a complement to, rather than a replacement for, human-centered safety strategies, ensuring that all road users feel secure and respected in shared environments (Ma et al., 2023; Kalašová, 2022).

The differing emotional responses and power dynamics observed in this study highlight the need for targeted interventions. Educational campaigns that emphasize the vulnerabilities of both pedestrians and drivers can help shift perceptions and reduce conflicts. Similarly, infrastructural changes, such as traffic calming measures and pedestrian-friendly designs, can help balance these dynamics by promoting shared responsibility and mutual respect on the roads (Ersan et al., 2020; Pradhan & Bhattacharya, 2020). Integrating these strategies into traffic policies will help create environments where both pedestrians and drivers can navigate safely and cooperatively.

4.6. Limitations and Future Directions

This study provides valuable insights into the dynamics of pedestrian and driver behaviors, particularly through the lens of dual-role users. However, several limitations must be addressed to refine our understanding and guide future research efforts. First, while the study offers a qualitative exploration of dual roles, it does not systematically examine demographic factors such as gender and age. Prior research indicates that these variables significantly shape road user behaviors. For instance, gender differences have been observed in traffic violations, with men typically engaging in riskier behaviors, while women are more likely to adhere to safety norms (Özkan & Lajunen, 2005; Öztürk & Öz, 2021). Similarly, age-related variations highlight that younger drivers often exhibit more aggression and impulsivity, while older drivers tend to prioritize caution (Dula & Ballard, 2003). Future research could incorporate these variables to uncover additional layers of behavioral complexity.

Cultural context is another critical dimension requiring further exploration. While this study primarily focuses on the Turkish context, cross-cultural studies could shed light on how different regulatory frameworks, cultural norms, and societal attitudes influence road user interactions (Péle et al., 2017). For instance, countries with stringent pedestrian rights regulations may experience fewer conflicts, whereas in other contexts, informal negotiation between pedestrians and drivers might dominate traffic interactions. Understanding these cultural variations could help develop globally adaptable interventions and region-specific traffic policies.

Moreover, the qualitative nature of this study poses limitations in generalizability. While rich, in-depth narratives were captured, the findings represent a specific sample and context. To build upon these insights, future research could develop new, culturally sensitive scales to assess the dynamics of dual-role road users. Existing instruments, such as the Driver Anger Scale (Deffenbacher et al., 2002), provide valuable frameworks but may not fully capture the nuances of pedestrian vulnerability or the dual-role dynamics explored here. Validating these scales across diverse cultural and demographic contexts would enhance their applicability.

Another avenue for future research is comparative studies. Comparing individuals who identify solely as pedestrians or drivers with dual-role participants could provide deeper insights into how role-specific experiences shape attitudes and behaviors. Such comparisons could also highlight discrepancies in the perception of vulnerability and power dynamics, offering actionable insights for targeted interventions.

Lastly, the study underscores the critical role of perceived vulnerability in shaping traffic interactions. Exploring how vulnerability influences road user behavior could lead to interventions that foster greater empathy and cooperation. For instance, educational programs emphasizing shared responsibilities and the reciprocal nature of road use could address tensions and promote safer interactions. Additionally, investigating how emerging technologies, such as automated vehicles and intelligent transport systems, impact these dynamics would provide a forward-looking perspective on traffic safety.

In summary, while this study lays a foundation for understanding dual-role road users, addressing these limitations through future research will enhance the depth and breadth of our knowledge. By integrating demographic, cultural, and technological dimensions, future studies can contribute to the development of inclusive, sustainable, and contextually relevant traffic systems.

Ethics Committee Approval Statement

Ethical approval for the research was obtained from the TOBB ETU Human Research Ethics Committee (No: E-27393295-100-52781).

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Araştırma Makalesi | Research Article

Psychological Impact of Horn Sounds and Headlight Flashing on Novice Drivers During Driving

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Abstract

This study investigates the psychological and behavioral responses of novice drivers to auditory and visual stimuli, specifically honking and headlight flashing. The primary objective of this study was to examine how novice drivers' emotional responses to environmental stimuli such as horn sounds and headlight flashing influence their driving behavior. Using face-to-face or online interviews, qualitative data were collected from 30 novice drivers, with a focus on their reactions to traffic stimuli and the resulting effects on their decision-making and overall driving performance. Thematic analysis was employed to identify key themes, resulting in five main categories: "Environmental Factors", "Emotional Responses", "Driver Behavior", "Communication", and "Attitudes." The findings reveal that external stimuli such as honking and headlight flashing significantly affect novice drivers' attention and emotional state, often leading to heightened levels of anxiety, anger, and stress. These emotional responses are closely linked to increased aggression on the road, including speeding, aggressive overtaking, and erratic lane changing. Furthermore, the study uncovered that novice drivers' attitudes toward these stimuli evolved with experience, with less emotional reactivity observed as they gained more driving experience. However, frequent exposure to these stimuli still led to a decrease in self-confidence in some cases. The results emphasize the importance of incorporating emotional regulation and stress management strategies into driver education programs. By equipping novice drivers with the skills to manage their emotional responses, it is possible to improve road safety, reduce aggressive driving behaviors, and enhance overall driving performance.

Anahtar Kelimeler: *novice drivers, psychological impact, horn sounds, headlight flashing, emotional responses*

Acemi Sürücülerde Korna Sesi ve Selektörün Sürüş Esnasındaki Olası Psikolojik Etkileri

Öz

Bu çalışma, acemi sürücülerin işitsel ve görsel uyaranlara, özellikle korna sesi ve selektöre verdikleri psikolojik ve davranışsal tepkileri incelemektedir. Bu çalışmanın temel amacı, acemi sürücülerin korna sesi ve selektör gibi çevresel uyaranlara verdikleri duygusal tepkilerin sürüş davranışlarına olan etkisini incelemektir. 30 acemi sürücü ile yüz yüze veya internet üzerinden görüşmeler yoluyla nitel veri toplanmış ve bu süreçte, acemi sürücülerin trafikte karşılaştıkları uyaranlara verdikleri tepkiler ile karar alma süreçleri ve genel sürüş performansları üzerindeki etkileri incelenmiştir. Katılımcılardan elde edilen veriler tematik analiz yöntemi kullanılarak beş ana kategori altında gruplandırılmıştır: "Çevresel Faktörler," "Duygusal Tepkiler," "Sürücü Davranışı," "İletişim" ve "Tutumlar." Bulgular, korna sesi ve selektör gibi dış uyaranların acemi sürücülerin dikkatini ve duygusal durumunu önemli ölçüde etkilediğini göstermektedir. Bu durum genellikle kaygı, öfke ve stres seviyelerinin artmasına yol açmaktadır. Bu duygusal tepkiler, hız yapma, agresif sollama ve şerit değiştirme gibi saldırgan sürüş davranışlarıyla yakından ilişkilidir. Ayrıca, acemi sürücülerin bu tür uyaranlara karşı tutumlarının zamanla değiştiği, deneyim kazandıkça duygusal tepkilerinin azaldığı tespit edilmiştir. Ancak, bu uyaranlara sık maruz kalmak bazı durumlarda sürücülerin özgüveninin azalmasına neden olabilmektedir. Çalışmanın sonuçları, sürücü eğitim programlarına duygu düzenleme ve stres yönetimi stratejilerinin dahil edilmesinin önemini vurgulamaktadır. Acemi sürücülerin duygusal tepkilerini kontrol edebilme becerisi kazanmaları, yol güvenliğinin artırılmasına, saldırgan sürüş davranışlarının azaltılmasına ve genel sürüş performansının iyileştirilmesine katkı sağlayabilir.

Keywords: *acemi sürücüler, psikolojik etki, korna sesi, selektör, duygusal tepkiler*

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Psychological Impact of Horn Sounds and Headlight Flashing on Novice Drivers During Driving

1. Introduction

Transportation has existed for centuries as the movement and transfer of people, goods, or information from one place to another. Transportation is divided into three main categories: road, air, and sea transportation. Among these, road transportation is commonly used for short-distance travel within cities and also for intercity travel, making it one of the most widely used transportation methods globally. Road traffic accidents occur when a vehicle collides with another vehicle, a pedestrian, an animal, or an object, generally resulting in injury, death, or property damage. The factors causing road traffic accidents are multifaceted, including human, environmental, and vehicle-related factors (Pérez-Acebo et al., 2021). The prevalence of road transportation contributes to the high number of vehicles and people on the road, as well as the varying quality of roads across countries.

According to the World Health Organization (2023), approximately 1.19 million people die each year due to road traffic accidents. In Turkey, in 2023, 88.9% of fatal road traffic accidents were caused by drivers, highlighting the urgent need for traffic safety measures (Turkish Statistical Institute, 2023). Furthermore, for the age group 5-29, road traffic accidents are the leading cause of death, ranking first among all other causes of death in this demographic. This aligns with the fact that novice drivers, which often include a large portion of young drivers, are particularly vulnerable to road traffic accidents. Although novice and young drivers are not synonymous, the majority of novice drivers fall within the young driver category. This group's high vulnerability to traffic accidents underscores the need for targeted interventions and safety measures, as they represent a significant portion of the population most at risk of fatal traffic accidents. In this context, the present study focuses on the psychological and behavioral effects of specific external stimuli—namely honking and headlight flashing—which may either be perceived as aggressive or be intentionally used with aggressive intent—on novice drivers. In this study, novice drivers are defined as individuals with limited driving experience, typically having driven less than 3000 kilometers. While the Turkish Ministry of Interior uses a two-year probationary period to define novice status (Republic of Turkey Ministry of Interior, 2015), prior research suggests that driving distance is a more accurate indicator of experience level (Al-Garawi et al., 2021). This study therefore adopts the criterion of driving less than 3000 kilometers to define novice drivers, as this threshold better reflects the cognitive and behavioral characteristics associated with inexperience.

To address concerns around conceptual clarity, it is important to note that while "driver behavior" and "aggressive driving" are terms that might occasionally be used interchangeably, in the current study a deliberate distinction is made. This study specifically focuses on honking and headlight flashing—actions that are commonly associated with aggressive driving. These behaviors may either be perceived as aggressive or be used with aggressive intent. Therefore, the research is conceptually framed within the context of aggressive driving. The terminology has been carefully chosen to reflect both observable traffic behaviors and the psychological processes underpinning these actions.

1.1. Aggressive Driving Behaviors among Novice Drivers

Aggressive driving behaviors are a significant and growing concern on roadways, particularly among novice drivers. These behaviors are characterized by actions that increase the risk of traffic collisions and endanger the safety of all road users. For novice drivers, inexperience often leads to risky behaviors such as illegal overtaking, tailgating, speeding, failure to signal, and failure to yield the right of way. In this study, honking and headlight flashing are treated as behaviors that may either be perceived as aggressive or be intentionally used with aggressive intent. Given their common association with aggressive driving, the study is conceptually framed within the context of aggressive driving. By focusing on this, the study aims to explore the effects of these specific behaviors, which are more likely to increase road safety risks among novice drivers. These behaviors can escalate into more dangerous actions, including running red lights and making sudden, unsafe lane changes. Novice drivers, due to their limited driving experience and unfamiliarity with road conditions, are especially vulnerable to engaging in these behaviors, which significantly heightens the risk of accidents (Day et al., 2018).

Research shows that although novice drivers typically exhibit a lower crash involvement rate during the initial months of driving, this tendency changes over time. As novice drivers gain more experience, their driving becomes more aggressive, contrary to the earlier observed reduction in accidents. This paradox suggests that gaining driving experience can sometimes lead to an increase in risk-taking behaviors rather than a decrease (Day et al., 2018). The shift in driving habits among novice drivers may be influenced by a combination of psychological factors, developmental stages, and external stressors encountered on the road (Harbeck & Glendon, 2018).

Interestingly, research indicates that while novice drivers may initially exhibit a lower crash involvement rate shortly after obtaining their licenses, this trend can reverse as they gain more experience. Studies have shown that as novice drivers accumulate driving hours, their likelihood of engaging in aggressive driving behaviors increases, leading to a higher incidence of accidents over time (Wayne & Miller, 2018; Ehsani et al., 2020). This paradox highlights the complex relationship between driving experience and risk-taking behavior, suggesting that increased familiarity with driving may embolden novice drivers to take greater risks rather than fostering safer driving habits (Yang et al., 2019).

1.2. Psychological Factors Influencing Aggressive Driving in Novice Drivers

Psychological factors such as frustration, impatience, and low emotional regulation are especially prevalent among novice drivers and contribute significantly to aggressive driving behaviors. Novice drivers, due to their limited experience, often struggle to manage emotions like frustration when faced with delays, heavy traffic, or other drivers' behavior, which can lead to aggressive reactions such as tailgating, speeding, or unsafe lane changes (Yang et al., 2019; Dula & Ballard, 2003). This emotional dysregulation is particularly concerning as it can escalate minor irritations into aggressive driving incidents, especially in high-stress driving environments (Yang et al., 2019).

The frustration-aggression hypothesis offers a valuable psychological framework for understanding how driving-related stressors can lead to aggressive behaviors. According to this theory, frustration from challenging driving conditions, such as congestion or poor visibility, can trigger aggression, particularly among novice drivers who are still developing the emotional regulation skills needed for safe driving (Kruglanski et al., 2023; Jovanović et al., 2011). In addition to emotional regulation, demographic factors like age and gender further complicate the relationship between psychological factors and aggressive driving. Studies consistently show that young drivers, especially males, are more prone to engage in risky driving behaviors due to personality traits such as dominance and impulsivity, which are strongly linked to aggressive driving (Rhodes & Pivik, 2011). Research also indicates that young drivers tend to report higher levels of aggressive driving compared to their older counterparts, underscoring their overrepresentation in traffic accidents (Ellison-Potter et al., 2001).

Novice drivers often struggle with poor situational awareness and decision-making due to limited driving experience. They may have narrower fields of vision and be less efficient at processing information from their environment compared to more experienced drivers (Fisher et al., 2006). This lack of experience, along with emotional regulation difficulties, can lead to poor judgment and risky driving behaviors, such as improper use of vehicle mirrors and failure to recognize potential hazards (McKnight & McKnight, 2003). The combination of emotional factors such as frustration and impatience, demographic influences, and the lack of driving experience significantly contribute to aggressive driving behaviors in novice drivers. Understanding these psychological dynamics is crucial for developing effective strategies to mitigate aggressive driving and enhance road safety.

1.3. Legal Interpretation of Horn and Headlight Use in the Context of Aggressive Driving

In Turkish traffic regulations, the use of horn and headlight flashing is permitted in specific circumstances. According to Article 56 of the Turkish Highway Code, the horn is to be used only when necessary to warn other drivers or avoid danger, and excessive or unnecessary use is prohibited. Similarly, headlight flashing is generally recognized as a communication tool but may be interpreted as aggressive or threatening depending on the context. In certain cases, such behaviors have been interpreted under Article 123 of the Turkish Penal Code as “disturbing the peace and tranquility of individuals”. While these behaviors are not inherently aggressive, their misuse or misinterpretation in real-world traffic can lead to conflict, stress, or risky maneuvers, especially among novice drivers. This duality underscores the importance of interpreting these stimuli both within legal definitions and psychological contexts.

1.4. The Role of Inexperience in Aggressive Driving and Traffic Accidents

Inexperience is a key factor contributing to aggressive driving behaviors and elevated crash risks among novice drivers. Due to limited exposure to diverse traffic scenarios, novice drivers often lack the ability to appropriately assess hazards or regulate their emotional responses in dynamic road environments (Chen et al., 2021). This gap in experience makes them more prone to stress, impulsive decision-making, and risky driving actions—especially when provoked by external stimuli such as honking or headlight flashing.

In their early driving years, novice drivers are more likely to engage in high-risk behaviors such as speeding, abrupt lane changes, or tailgating—actions that align with definitions of aggressive driving (Drummond, 1989; Scialfa et al., 2011). Their underdeveloped judgment and slower response to unexpected events contribute significantly to this trend. The likelihood of traffic accidents is especially high during this period, as hazard perception and situational awareness skills are still in development (Rashid & Ibrahim, 2017; Scialfa et al., 2011). Additionally, novice drivers often experience cognitive overload, which impairs their ability to process environmental cues effectively and respond in a timely manner. This can lead to misinterpretations of other drivers' intentions or external signals—further escalating the risk of aggressive reactions or unsafe maneuvers (Smith et al., 2009; Castro et al., 2014; Žardeckaitė-Matulaitienė et al., 2018).

Although experience improves hazard perception and reduces cognitive strain over time, the early driving period remains the most vulnerable phase. Addressing this vulnerability through targeted training programs and behavioral interventions is essential for mitigating aggressive driving tendencies and improving novice driver safety.

1.5. Situational Factors and Aggressive Driving in Novice Drivers

Situational factors significantly contribute to the emergence of aggressive driving behaviors, particularly among novice drivers who are still developing the skills necessary for adaptive decision-making under pressure. One of the most influential situational stressors is traffic congestion. In congested conditions, novice drivers often experience heightened levels of frustration, which can result in impulsive decisions such as speeding, failing to yield, or aggressively overtaking other vehicles. These reactions are closely aligned with definitions of aggressive driving and are exacerbated by the novice driver's limited ability to evaluate and adapt to complex traffic environments (Lazuras et al., 2019).

Research by Jovanović et al. (2011) reinforces the link between situational stress and aggression, showing that traffic-induced frustration can escalate into overtly aggressive behavior. This pattern supports the frustration-aggression hypothesis, which posits that perceived obstacles to goal achievement—such as delays or obstructions—can trigger aggressive reactions, especially in individuals with underdeveloped coping mechanisms. For novice drivers, these emotional responses may be particularly difficult to regulate, resulting in heightened risks for both themselves and others on the road.

1.6. Aim of the Study

Although studies have shown that novice drivers tend to overestimate their driving abilities and engage in riskier behaviors, resulting in more aggressive driving, it is equally true that their inexperience also causes them to allocate more of their cognitive resources to driving tasks. This often makes it easier for their attention to become distracted compared to more experienced drivers. Exposure to behaviors like honking and flashing headlights, and the ability to interpret the messages embedded in these stimuli, requires novice drivers to engage in multiple cognitive tasks simultaneously, a challenge they are less equipped to handle. This study aims to investigate the psychological effects of honking and headlight flashing, which might be perceived as aggressive external stimuli, on novice drivers.

2. Method

2.1. Participants

The study included 30 participants (15 males, 15 females) aged between 21 and 30 years (M = 23.2, SD = 2.54). Female participants reported an average age of 23.8 years (SD = 2.89), whereas the average age for male participants was 22.6 years (SD = 2.11). All participants held a valid driving license, with the duration of ownership ranging from 1 to 8 years. This criterion ensured participants could reflect on their experiences as both drivers and pedestrians.

Participants were primarily from Ankara, İzmir, Konya, and other metropolitan cities in Turkey. The research was announced through social media platforms using a snowball sampling method. In the initial invitation, participants were asked to share the study announcement with others who might meet the participation criteria. To be included in the study, individuals had to (1) be aged between 18–30, (2) have held a driver's license for less than two years or driven less than 3000 kilometers, and (3) not have intensive professional driving experience (e.g., as a taxi or delivery driver). These criteria were explicitly stated in the recruitment announcement. As such, no interested participants were excluded, as those not meeting the requirements did not proceed with participation.

Participants' driving behaviors varied based on the time intervals they reported spending in traffic. As summarized in Table 1, driving patterns revealed notable gender-based and individual differences. For instance, male participants predominantly reported driving during Afternoon Only, while female participants showed greater variability, often indicating multiple time periods or responses such as "It depends." Combined categories like "Afternoon + Evening" and "Morning + Afternoon" showed more balanced participation across genders.

On average, participants drove 1206 kilometers (SD = 885) monthly, with male participants reporting slightly longer distances (M = 1250 km, SD = 910) compared to females (M = 1162 km, SD = 860). Traffic density perceptions also varied: 60% of participants described their driving environments as Moderate, with the remaining indicating Heavy, Very Heavy, or Light density levels.

The sample size of 30 participants was selected to balance the depth and breadth of responses, ensuring sufficient diversity while allowing recurring themes to emerge. This approach aligns with qualitative research methodologies, which prioritize the richness of data over sheer numerical representation. Malterud et al. (2016) suggest that smaller samples can yield valuable insights if saturation is achieved, while Vasileiou et al. (2018) highlight the importance of justifying sample size sufficiency in interview-based studies.

This diverse yet focused sample enabled an in-depth exploration of time-based driving experiences and the factors influencing novice drivers. By purposefully selecting participants based on relevant criteria, the study supports the notion that qualitative research can effectively use smaller sample sizes to achieve meaningful results (Malterud et al., 2016; Vasileiou et al., 2018). Aligned with qualitative research guidelines, which suggest saturation is typically reached with 12 to 20 interviews (Braun & Clarke, 2006), the sample size of 30 allowed for a robust examination of participants' experiences and the identification of significant themes. The larger sample also enhanced the diversity of perspectives while maintaining the depth needed for meaningful insights.

2.2. Instruments

Data were collected through demographic information form and semi-structured interviews. The demographic form included questions regarding participants' age, gender, duration of driving license ownership, and the monthly distance driven in kilometers. This background information was essential for contextualizing participants' responses and identifying patterns related to their demographic characteristics and driving behaviors.

The semi-structured interview guide consisted of 16 open-ended questions designed to explore the psychological and behavioral effects of auditory and visual stimuli during driving, with a particular focus on vehicle horn and headlight usage. The questions were developed based on environmental psychology frameworks and previous research examining the impact of external stimuli on drivers' cognitive and emotional states (Takada et al., 2017; Balk & Tyrrell, 2011). Additionally, the transactional-cognitive theory of stress served as the theoretical foundation, highlighting how individuals assess and respond to environmental demands based on their perceived ability to cope (Lazarus & Folkman, 1984).

The interview questions aimed to capture participants' experiences and perceptions across several dimensions, including environmental factors that cause discomfort while driving, the psychological effects of horn and headlight stimuli, and their influence on driving behaviors and decision-making processes. For instance, participants were asked, "What environmental factors disturb you the most while driving?" and "How do horn and headlight stimuli affect your confidence while driving?" Emotional and social implications of these stimuli were also explored with questions such as, "What do you think about drivers who frequently use horns or headlights in traffic?" This comprehensive approach ensured diverse perspectives were included, facilitating an in-depth understanding of how external stimuli influence drivers' psychological states and behaviors.

Table 1. Characteristics of participants

ID	Age	Gender	Education	License	Active Driving Status	Distance Driven (km)	Traffic Density Perception	Time Intervals	City
1	22	Male	High school	1	Occasionally	300	Moderate	Afternoon	Ankara
2	23	Male	High school	1	No	2000	Heavy	Night	Ankara
3	24	Male	Bachelor's	2	No	1500	Moderate	It depends	Ankara
4	22	Male	High school	3	Occasionally	2000	Moderate	Afternoon	Aydın
5	21	Male	High school	1	Occasionally	1000	Moderate	Evening	İzmir
6	21	Female	High school	3	Yes	1500	Moderate	It depends	Ankara
7	22	Female	Bachelor's	3	Occasionally	1000	Moderate	It depends	İzmir
8	22	Male	Bachelor's	1	Occasionally	2700	Very heavy	Morning, Afternoon	İzmir
9	27	Female	Bachelor's	6	Yes	700	Moderate	Morning, Afternoon, Evening	Konya
10	22	Female	High school	4	Yes	40	Heavy	Morning, Evening	Ankara
11	23	Female	High school	4	Yes	1500	Heavy	Afternoon, Evening, Night	Konya
12	24	Female	High school	6	Yes	2800	Moderate	Afternoon, Night	Ankara
13	22	Female	High school	3	Yes	3000	Moderate	Afternoon, Evening	Ankara
14	21	Female	High school	2	Yes	1000	Heavy	Afternoon, Evening	Ankara
15	26	Female	Bachelor's	7	Occasionally	60	Moderate	Morning	İzmir
16	27	Female	Bachelor's	6	Yes	1000	Moderate	Afternoon	İzmir
17	21	Male	High school	1	Yes	900	Heavy	Morning	Konya
18	23	Female	Bachelor's	3	Yes	420	Moderate	Afternoon	Konya
19	30	Female	Bachelor's	8	Yes	1000	Moderate	Morning, Afternoon	Mersin
20	28	Female	Bachelor's	5	No	30	Moderate	Night, Evening	İzmir
21	22	Male	High school	3	Occasionally	800	Moderate	Afternoon, Evening	Edirne
22	23	Female	High school	4	Yes	800	Moderate	Morning, Evening, Night	Konya
23	22	Female	High school	4	Occasionally	2000	Light	Evening, Night	Trabzon
24	23	Male	High school	4	Occasionally	2000	Moderate	Morning, Afternoon, Evening, Night	İzmir
25	22	Male	High school	1	Yes	1800	Light	Afternoon, Evening, Night	Aydın
26	23	Male	High school	1	No	15	Light	Afternoon	Ankara
27	22	Male	High school	2	Yes	600	Moderate	Afternoon	Antalya
28	23	Male	Bachelor's	4	Yes	2500	Moderate	Evening	Ankara
29	22	Male	High school	3	Yes	2000	Moderate	Afternoon	Malatya
30	22	Male	Bachelor's	4	Yes	1000	Very heavy	Evening, Night	İstanbul

2.3. Procedure

Participants were recruited for the study using a snowball sampling method. Informed consent was obtained from all participants, emphasizing the voluntary nature of their participation and ensuring they understood the study's objectives and their rights. Interviews were conducted on a one-on-one basis, either face-to-face or online, based on the participants' preferences and convenience. The duration of the interviews ranged from 20 to 30 minutes. For participants who consented, audio recordings were made to ensure accuracy during transcription and analysis. In cases where participants declined audio recording, detailed notes were taken by the interviewer.

The semi-structured interview guide, as outlined in Section 2.2, was used to explore participants' experiences and perceptions regarding auditory and visual stimuli in traffic, with a particular focus on vehicle horn and headlight usage. This approach ensured consistency across interviews while allowing participants to express their perspectives freely. The data collected from these interviews were then analyzed using thematic analysis, as described in the following section.

2.4. Data Analysis

The collected data were analyzed using thematic analysis, following the six-phase framework outlined by Braun and Clarke (2006). In the first phase, interviews were transcribed verbatim for participants who consented to audio recordings, while for those who did not consent to recordings, detailed notes were used as the primary data source. The transcripts and notes were read multiple times to ensure familiarity with the data and to capture initial impressions.

In the second phase, initial codes were generated inductively, focusing on recurring patterns and significant elements in the participants' responses. These codes were then grouped into overarching themes and subthemes, reflecting the psychological, social, and behavioral dimensions of participants' experiences with auditory and visual stimuli in traffic. To ensure reliability and consistency, the identified themes were reviewed iteratively by three researchers, with at least two researchers agreeing on the final coding and theme structure.

An inductive and semantic approach was employed throughout the analysis, prioritizing the explicit responses of participants over interpretive assumptions. Direct quotations from participants were used to support the identified themes, ensuring the findings remained grounded in the data. This approach facilitated a comprehensive understanding of how environmental stimuli, such as horns and headlights, influence drivers' psychological states and behaviors, contributing to the broader objectives of the study.

3. Results

The data obtained from participants' responses were analyzed using thematic analysis and classified under five main themes: "Environmental Factors," "Emotional Responses," "Driver Behavior," "Communication," and "Attitudes." In the "Driver Behavior" theme, two subthemes were identified: "Response to Stimuli" and "Driver's Use of Stimuli." Additionally, in the "Attitudes" theme, three subthemes were identified: "Attitudes Toward Others," "Attitudes Toward Own Driving," and "Experience-based Changes in Attitudes." Example quotes from participants are provided throughout the text to illustrate the themes and subthemes.

Table 2. Themes, subthemes and categories

Main Theme	Categories
Environmental Factors	Impact of Environmental Factors
Emotional Responses	Emotional Responses
Driver Behavior	Response to Stimuli, Driver's Use of Stimuli
Communication	Facilitating Communication, Hindering Communication
Attitudes	Attitudes Toward Others, Attitudes Toward Own Driving, Attitudes Changing with Experience

3.1. Environmental Factors

Participants mentioned the impact of environmental factors during the interviews. The overwhelming presence, excessive intensity, or sudden occurrence of environmental factors affect the driving performance of novice drivers. According to the interview results, the inappropriate behaviors of other drivers (such as changing lanes without signaling, failing to maintain lane discipline, high speeds, sudden lane switching, etc.) were observed as the most significant environmental factors affecting novice drivers' performance. The dangerous driving behaviors of other drivers impact traffic safety and create a risk of accidents. Environmental factors such as lighting, sound, roadworks, temperature, pedestrian behaviors, heavy traffic, and noise also influence driver behavior.

"*Suddenly appearing pedestrians or animals, vehicles that change lanes abruptly or brake suddenly distract my attention. Sometimes, conversations inside the car also distract me.*" (P2, 22, Male)

"*The most disturbing factors for me are drivers who don't signal, those who do not follow lane discipline, roads altered due to construction, and noises at such a high level that I cannot understand traffic warnings.*" (P11, 23, Female)

3.2. Emotional Responses

Looking at the responses given by participants, honking the horn creates nervousness and fear for most participants. Flashing headlights, on the other hand, often results in anger. Some participants stated that they did not experience any change in their emotional state. Participants question the reasons for and the context in which they are honked at or flashed at. The emotional responses given can also influence their behaviors. In night driving, participants tend to perceive these stimuli as a form of warning and respond positively to other drivers.

"*I get nervous when they honk at me. I check what I did wrong.*" (P9, 22, Female)

"*I get angry because I try to follow the rules, but when I see headlights, I wonder, 'What happened now?'*" (P16, 21, Female)

"*I don't mind honking or flashing headlights, I stay calm.*" (P1, 21, Male)

Participants' emotional states during the day depend on how much they are exposed to these stimuli while driving. If they are exposed to honking and flashing lights frequently, they may feel angry or stressed during the day. However, they also mention that as they gain experience, the impact of these events on their emotional state decreases. Some participants indicated that their emotional responses do not affect how they feel throughout the day.

"*It doesn't affect me that much anymore. I used to feel nervous when I was a beginner, but now I'm used to it. It always happens the same way; I can't change people.*" (P19, 30, Female)

"*No. I forget about it after I get out of the car.*" (P23, 22, Female)

Participants who believe they have engaged in behaviors that would anger other drivers generally approach such situations with understanding. However, some drivers get angry in these situations.

"*When someone is driving slowly in front of me, I try to be understanding. They might be a new driver or an older driver.*" (P7, 22, Female)

"*When another driver does this to me, I get tense and either don't let them pass or intervene in the conflict.*" (P27, 22, Male)

3.3. Driver Behavior

The statements obtained from the interviews relate to both the responses of participants to horn and headlight usage by other drivers and their own use of these stimuli. The "Driver Behavior" theme has two subthemes: "Response to Stimuli" and "Driver's Use of Stimuli."

3.3.1. Response to stimuli.

Participants stated that when they perceive a horn or headlight, they increase their attention and believe they have made a driving mistake, prompting them to change their behavior. However, when they think they are driving according to the rules and the other driver is approaching aggressively, they do not change their driving. Those who change their behavior generally move to the right lane, speed up, or check their surroundings. Moreover, the majority of participants stated that they tend to make quicker decisions after being exposed to these stimuli.

"*Of course, my attention is distracted. I try to understand what the person behind me is saying. Nowadays, people do this for anything. So, I first correct my concentration on the road and then try to understand.*" (P10, 21, Female)

"*Definitely, my decision-making speed is affected; I try to make decisions much faster.*" (P25, 22, Male)

"*If I think I've made a mistake, I act according to the appropriate behavior based on my traffic knowledge.*" (P17, 21, Male)

3.3.2. Driver's use of stimuli.

Participants described the situations in which they use the horn or flash headlights, mainly to attract the attention of other vehicles, respond to incorrect behaviors from other drivers, warn other vehicles, or when driving on narrow streets or side roads. While all users use the horn, some participants indicated they do not use the headlights.

"*When I'm passing through side roads, on a narrow street, or when I'm in the left lane and a fast vehicle is behind me.*" (P20, 22, Female)

"*When I think the attention of other road users is distracted, I honk to make them aware of my presence*." (P6, 23, Female)

About half of the participants believe they sometimes perform behaviors that might anger other drivers. These behaviors include driving slower than other vehicles, failing to signal, or changing lanes improperly. However, some participants think they are not the ones making drivers angry but rather that the other drivers are impatient.

"*No, I don't think so. If they get angry, I think it's not because of something I did, but because they are impatient.*" (P29, 22, Male)

"*Sometimes, I think I make other drivers angry. For example, I drive slower than other drivers, or when I park, there might be space for another car.*" (P6, 22, Female)

3.4. Communication

Participants noted that horn and headlight use both facilitated and complicated communication in traffic. They emphasized that the purpose of using these stimuli was key. Some participants stated that horn and headlight usage was the only communication method in traffic, contributing to smoother traffic flow. They also stated that using the horn to express gratitude positively affected communication. Other participants mentioned that horn and headlight usage should not be used for communication purposes, as any use in traffic should be considered inappropriate.

"*I think both sides are cursing at each other. But flashing headlights feels more polite than honking the horn.*" (P9, 22, Female)

"*I think it has a positive effect. There is no other way to communicate while driving, and even if I make a mistake, it lets me know*." (P8, 23, Male)

3.5. Attitudes

Based on the interviews, the Attitudes theme was examined under three subthemes: "Attitudes Toward Others," "Attitudes Toward Own Driving," and "Experience-based Changes in Attitudes."

3.5.1. Attitudes toward others.

Participants in the study thought that the timing of horn and headlight usage by other drivers was what mattered most. They described drivers who use these stimuli at inappropriate times as aggressive and impatient. However, they had a positive attitude toward drivers who used them in necessary situations. Some participants also noted that horn usage caused noise pollution and affected their attention.

"*Sometimes I think it is used unnecessarily. It is used just to express hatred.*" (P21, 23, Male)

"*I think positively about drivers who use it when necessary. But I think honking excessively or using the horn when it is not necessary (such as honking immediately when the traffic light turns green) is wrong.*" (P28, 22, Male)

One participant, unlike the others, mentioned having a bias against drivers who use horns and headlights, thinking they are often male.

"*I develop a bias that they are impatient or that they are male.*" (P12, 22, Female)

3.5.2. Attitudes toward own driving.

Participants who were exposed to honking or flashing headlights stated that in their early driving experiences, their confidence dropped, and they felt like bad drivers. As they gained more driving experience, the impact of these stimuli on their confidence decreased, and they thought it would continue to lessen. However, frequent exposure to these stimuli could still lead to a loss of confidence, even for more experienced drivers. Some participants stated that when they made a mistake, they tried not to repeat it.

"*It has a negative effect because I always blame myself for the mistake.*" (P16, 21, Female)

"*When I am exposed to these stimuli repeatedly, my confidence decreases. These stimuli cause panic and stress. However, when my driving performance decreases, being exposed to these stimuli serves as an important warning for me.*" (P17, 21, Male)

3.5.3. Experience-based changes in attitudes.

Participants mentioned that as they gained more driving experience, their attitudes toward external stimuli (such as honking or flashing headlights) evolved. While initially these stimuli would make them feel nervous or self-conscious, over time they became less affected by them. However, frequent exposure to such stimuli could still negatively affect their confidence. Some participants also noted that the source of the stimuli (e.g., male drivers) influenced how it impacted their confidence.

"*It doesn't affect me that much anymore. I used to feel nervous when I was a beginner, but now I'm used to it. It always happens the same way; I can't change people*." (P19, 30, Female)

"*Because I think I am a novice driver, I get nervous when I'm exposed to these stimuli, and this situation decreases my confidence. Also, the gender of the driver matters to me. If these stimuli come from male drivers, it damages my confidence even more.*" (P18, 22, Female)

4. Discussion

In this study, the findings reveal the psychological and behavioral responses of drivers to auditory and visual stimuli, particularly honking and headlight flashing. The qualitative data collected from participants through interviews were organized under five main themes: "Environmental Factors," "Emotional Responses," "Driver Behavior," "Communication," and "Attitudes." Each main theme was further divided into relevant subthemes. Specifically, the "Driver Behavior" theme included two subthemes: "Response to Stimuli" and "Driver's Use of Stimuli." Similarly, the "Attitudes" theme was broken down into three subthemes: "Attitudes Toward Others," "Attitudes Toward Own Driving," and "Attitudes Changing with Experience."

4.1. Environmental Factors

The first theme, "Environmental Factors," highlights the critical role external elements play in driving performance, especially for novice drivers. As Ni et al. (2024) noted, factors such as night driving, winding roads, and traffic congestion significantly increase stress levels in drivers. Our study confirms that environmental factors play a pivotal role in disrupting the attention of drivers, particularly for those with less experience. External stimuli not only divert attention but also force drivers to allocate more cognitive resources to basic driving tasks, as seen with novice drivers. Research by Lee (2007) supports this finding, showing that inexperienced drivers are more susceptible to distraction-related accidents due to their limited attention capacity. Inexperienced drivers also struggle with managing unexpected situations because they are still developing automatic driving skills (Lansdown, 2002). As such, external stressors, whether from road conditions or other drivers, significantly impair driving performance and safety. The implications of this are clear: raising awareness of environmental factors in driver training programs, particularly for novice drivers, can help reduce accidents caused by distraction and stress. Furthermore, programs should address techniques for better coping with environmental stressors to improve road safety.

4.2. Emotional Responses

The second theme, "Emotional Responses," centers on how auditory and visual stimuli like honking and flashing headlights trigger emotional reactions, which in turn influence driver behavior. Emotional responses, particularly drivers' ability to regulate emotions in stressful traffic situations such as flashing lights or congestion, significantly affect driving behavior. Wu et al. (2018) found that higher emotional control skills were associated with fewer aggressive reactions and accidents, suggesting that emotional regulation plays a protective role in challenging driving conditions. However, our findings show that novice drivers demonstrate heightened emotional reactions to stimuli like honking, with many participants reporting feelings of anger, anxiety, and tension. This heightened emotional response has been linked to an increase in risky driving behaviors, such as speeding or aggressive overtaking, as noted by Deffenbacher et al. (2003). High anxiety levels hinder cognitive processing and motor tasks, which could elevate the risk of accidents, especially for younger and less experienced drivers. To mitigate these emotional responses, it is crucial to incorporate emotional intelligence and stress management training into driver education. By helping novice drivers better understand and regulate their emotional responses to stressful situations, we can promote safer, more composed driving behaviors.

4.3. Driver Behavior

The third theme, "Driver Behavior," reveals that auditory and visual stimuli, such as honking and headlight flashing, not only affect the emotional state of drivers but also influence their subsequent behavior on the road. This theme was divided into two subthemes: "Response to Stimuli" and "Driver's Use of Stimuli." Our study showed that most participants assess whether they made a mistake when they hear a horn or see headlights flashing and adjust their behavior accordingly. The nature of the response depended on whether the stimulus was deemed necessary or unnecessary. For example, participants typically responded to honking by changing lanes or accelerating, while headlight flashing was often interpreted as a "move out of the way" signal. For instance, research by Dula and Geller (2003) emphasizes that aggressive driving behaviors, including honking, are often linked to feelings of anger and perceived injustices on the road. Their study found that drivers frequently resort to honking as a form of retaliation or to express their displeasure in response to other drivers' actions, reinforcing the notion that honking serves as a communication tool in high-stress driving situations. On the other hand, headlight flashing was more commonly used to request or demand compliance from other drivers, further reflecting the communicative power of these stimuli. While the appropriate use of honking and headlight flashing can improve safety by alerting other drivers to potential risks, misuse can lead to panic, distraction, and confusion. This suggests that educating drivers on the proper use of these stimuli is crucial in ensuring they do not inadvertently contribute to road safety risks.

4.4. Communication

The fourth theme, "Communication," emphasizes how honking and headlight flashing serve as forms of communication on the road. Research by Takada et al. (2017) highlighted that honking, when used inappropriately, may be perceived as an ineffective communication tool due to the lack of clear, universally understood messages. Our findings, however, suggest that honking and headlight flashing play a significant role in traffic communication, provided they are used in the right context. Participants reported that honking to signal danger or indicate presence helped facilitate smoother traffic flow, whereas excessive honking or using it in the wrong context created tension and aggression. This aligns with the findings of Berdoulat et al. (2013), who discusses how impulsivity and emotional responses, such as anger, can lead to aggressive driving behaviors, including the use of the horn. Hence, there is a need for clearer guidelines and training on how these stimuli should be used to foster safer and more effective communication in traffic.

4.5. Attitudes

The final theme, "Attitudes," explores the development of attitudes toward other drivers and one's own driving performance, especially in relation to honking and flashing headlights. This theme was divided into three subthemes: "Attitudes Toward Others," "Attitudes Toward Own Driving," and "Attitudes Changing with Experience." Our study found that drivers' attitudes toward others were shaped by the context and appropriateness of honking and headlight flashing. When these stimuli were used correctly, participants viewed the behavior of the other driver positively. Conversely, inappropriate or excessive use was often seen as aggressive, leading to negative perceptions of the driver. Interestingly, some participants associated frequent use of these stimuli with impatience or even gendered stereotypes, specifically linking them to male drivers. Concerning their attitudes toward their own driving, many participants reported a decrease in self-confidence when exposed to honking or flashing headlights, particularly when they perceived themselves as at fault. However, with more driving experience, the emotional impact of these stimuli decreased, and drivers became more confident and less reactive. These findings suggest that exposure to these stimuli over time can reduce their emotional impact, and that more experienced drivers may become less anxious and more self-assured. Therefore, incorporating strategies to reduce emotional responses to external stimuli can not only improve novice drivers' attitudes toward their own driving but also contribute to better overall performance.

4.6. Practical Implications

The findings of this study have several practical implications for improving road safety, particularly for novice drivers. Firstly, the study highlights the importance of incorporating emotional regulation and stress management training into driver education programs. By equipping novice drivers with strategies to cope with emotional stimuli like honking and headlight flashing, they can become more composed and safer drivers. Additionally, training programs should focus on improving risk perception and communication skills, especially in stressful driving environments such as traffic congestion. Educating drivers on the proper use of auditory and visual stimuli can help reduce confusion and road aggression. Moreover, the study suggests that awareness campaigns about the psychological impacts of environmental factors and emotional responses can enhance drivers' overall performance and reduce accidents.

A comprehensive approach that includes emotional regulation training, risk perception enhancement, educational campaigns, and simulator-based training can significantly reduce aggressive driving behaviors among novice drivers. By equipping young drivers with the necessary skills and knowledge to navigate the complexities of driving, we can improve road safety and reduce the incidence of aggressive driving.

4.7. Theoretical Implications

This study contributes to the growing body of research on aggressive driving behaviors by providing a comprehensive analysis of the psychological and emotional responses to environmental stimuli, particularly honking and headlight flashing. The findings support the frustration-aggression hypothesis, showing that environmental stressors can elicit aggressive responses. Furthermore, the study emphasizes the role of emotional intelligence in driving safety, offering a theoretical framework for incorporating emotional regulation and cognitive coping strategies into traffic psychology research. This research also advances our understanding of the interaction between emotional and cognitive factors in driving behavior, particularly for novice drivers.

A comprehensive approach that includes emotional regulation training, risk perception enhancement, educational campaigns, and simulator-based training can significantly reduce aggressive driving behaviors among novice drivers. By equipping young drivers with the necessary skills and knowledge to navigate the complexities of driving, we can improve road safety and reduce the incidence of aggressive driving.

4.8. Emergent Findings

The study primarily examined novice drivers' psychological and behavioral responses to honking and headlight flashing, several unexpected but valuable themes emerged from the participants' narratives. Female participants frequently mentioned feeling more affected when exposed to aggressive behaviors from male drivers. This may suggest an underlying influence of social power dynamics and perceived gender-based patterns in Turkey. Also, several participants described engaging in passive-aggressive or retaliatory behaviors, noting that they felt disturbed by another driver's actions, they sometimes intentionally mirrored those actions to express their anger. This revealed behavioral patterns that, while not considered as performance indicators, provide insights into novice drivers' adaptive responses.

Horn and headlight flashing were not interpreted uniformly. While some participants viewed these signals as helpful for communication and correction, others experienced them as unnecessary and frightening. These differences may show subjectivity in traffic communication and lead to misunderstandings, which could potentially escalate into accidents or road conflicts.

In addition, it was observed that participants gradually normalized aggressive driving experiences. They described stress and aggression in traffic as something normal or part of a routine. This normalization in traffic may lead to emotional desensitization or reduced sensitivity to risky driving cues. Some participants stated that they developed personal coping strategies—such as internal self-talk, humor, or calming techniques—to deal with repeated exposure to stressful stimuli. These coping strategies suggest a psychological adaptation process in novice drivers navigating challenging traffic environments. Finally, some participants noted that non-verbal cues such as body posture, exaggerated hand gestures, and vehicle positioning offered alternative ways of interpreting the reasons behind honking or headlight flashing. This observation highlights the importance of novice drivers taking situational cues into account when evaluating the behaviors of other drivers.

4.9. Limitations and Future Research

While this study provides valuable insights into the psychological and behavioral responses of novice drivers, there are several limitations that should be addressed in future research. The sample size was relatively small, and the participants were primarily drawn from a specific demographic, which may limit the generalizability of the findings. Future studies could expand the sample size and include drivers from diverse age groups and backgrounds to gain a broader perspective on the issue. Additionally, the study relied on self-reported data, which may be subject to biases such as social desirability or recall bias. Moreover, the use of different communication modes (i.e., video conferencing and face-to-face interviews) may have influenced participants' responses, particularly in terms of emotional expression and perceived anonymity. This variation in interview settings should be acknowledged as a methodological limitation, as differences in setting might have influenced participants' ability to express their ideas comfortably, this could have potentially led to bias. Using observational methods or in-vehicle data collection could provide more objective insights into driver behavior. Lastly, future research should explore the long-term effects of training programs aimed at reducing emotional responses and improving risk perception, as well as the effectiveness of these programs in real-world driving scenarios. Exploring the impact of different interventions, such as mindfulness training or cognitive-behavioral therapy, could also offer new avenues for improving novice driver safety.

Ethics Committee Approval Statement

Ethical approval for the research was obtained from the TOBB ETU Human Research Ethics Committee (E-27393295-100-69434).

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Araştırma Makalesi | Research Article

Analysis Of Traffic Accidents Using Machine Learning Under Pandemic Conditions

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Abstract

The COVID-19 pandemic that emerged in 2019 affected all aspects of life, including spiritual, psychological, social, economic, health and transportation aspects. Despite its negative consequences, however, the COVID-19 pandemic also produced some positive results. This study investigated the effect of COVID-19 lockdowns on killed-and-injured traffic accidents in metropolitan cities and Zonguldak Province in Turkey from 2012–2019 using the Extreme Gradient Boost (XGBoost) algorithm. Nonlinear regression analyses were performed using machine learning in Python programming language on the Google Colab platform. The analysis provided an estimated number of accidents for 2020, which was compared with the real killed-and-injured accidents data from metropolitan cities and in Zonguldak in 2020. The comparison showed that COVID-19 lockdowns caused a decrease in traffic accidents in metropolitan cities and Zonguldak Province, except in Diyarbakır and Ordu. It has been revealed that the number of traffic accidents predicted by machine learning algorithms in metropolitan areas for 2020 is 18.3% higher than the number of traffic accidents in 2020. Therefore, although accurate predictions can be made with machine learning, it has been observed that there may be a margin of error in extraordinary situations such as earthquakes, wars and pandemics.

Keywords: Lockdown, traffic accidents, accident prediction model, machine learning, extreme gradient boost

Makine Öğrenmesi Algoritmalarını Kullanılarak Pandemi Şartları Altında Trafik Kazalarının Analizi

Öz

2019 yılında ortaya çıkan COVID-19 pandemisi, ruhsal, psikolojik, sosyal, ekonomik, sağlık ve ulaşım olmak üzere hayatın tüm alanlarına etki ettiği gözlemlenmiştir. COVID-19 'dan kaynaklı pandemi süreci birçok olumsuz sonuçlarına rağmen, bazı olumlu sonuçlar da doğurmuştur. Bu çalışmada, pandemi sürecinin olumlu sonuçlarından biri detaylı olarak ele alınmıştır. Çalışma, Türkiye'de Zonguldak ili de dahil olmak üzere tüm büyükşehirleri kapsamaktadır. Bu çalışma ile, COVID-19 karantinalarının 2012-2019 yılları arasında gerçekleşen ölümlü ve yaralanmalı trafik kazaları üzerindeki etkisi, Extreme Gradient Boost (XGBoost) algoritması kullanılarak detaylı olarak araştırılmıştır. Google Colab platformunda Python programlama dilinde makine öğrenmesi kullanılarak doğrusal olmayan regresyon analizleri yapılmıştır. Analiz sonucunda 2020 yılı için tahmini kaza sayısı elde edilmiş ve bu sayı 2020 yılında büyükşehirlerde ve Zonguldak'ta meydana gelen gerçek ölümlü ve yaralanmalı kaza verileri ile karşılaştırılmıştır. Bu analiz, COVID-19 karantinalarının Zonguldak, Diyarbakır ve Ordu illeri hariç tüm büyükşehirlerde trafik kazalarında azalmaya neden olduğunu göstermiştir. Makine öğrenimi algoritmaları ile 2020 yılı için büyükşehirlerde tahmin edilen trafik kaza sayılarının, 2020 yılında gerçekleşen trafik kaza sayılarına göre %18,3 oranında daha yüksek olduğu ortaya çıkmıştır. Dolayısıyla Makine öğrenmesi ile doğru tahminler yapılabilse de deprem, savaş ve pandemi gibi olağanüstü durumlarda hata payı olabileceği gözlemlenmiştir.

Anahtar Kelimeler: Karantina, trafik kazaları, kaza tahmin modeli, makine öğrenmesi, extreme gradient boost

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Analysis of Traffic Accidents Using Machine Learning Under Pandemic Conditions

1. Introduction

Worldwide innovations and developments directly affect freight and passenger mobility. Increasing population, developing technology and increasing trade and communication opportunities have augmented the importance of transportation activities each day (Gökdağ et al., 2004; Jovic Vranes et al., 2018). Competition in the world markets has accelerated the development of transportation activities and companies that want to increase their market share need to provide increasingly more transportation services (Bayraktutan & Özbilgin, 2013).

While the population in Turkey increased at an annual average rate of 1.4% between 2012 and 2019, it increased by only 0.6% in 2020 compared to 2019. This rate of increase was the lowest annual rate of the last 60 years (World Health Organization [WHO], 2019)). However, the annual average increase in the number of motor vehicles has been 4.4% since 2012. The increasing population, number of registered vehicles and people with driver's licenses and speed and competition of development in the transportation sector, as well as the trend toward a more mobile lifestyle, have increased traffic density greatly. Thus, the safety of traffic has also been significantly impacted. According to the WHO, one person dies every 24 seconds on the road worldwide. Traffic accidents, which are the eighth leading cause of death (Selimoğlu, 2014; WHO, 2019), cause annually the deaths of 1.35 million worldwide, and between 20–50 million people experience non-fatal injuries.

The COVID-19 pandemic that emerged in 2019 and was announced on 11 March 2020 in Turkey (WHO, 2019) affected the whole world in all aspects of life, including material, spiritual, psychological, social, economic, health and transportation aspects. In Turkey, all schools, including universities, began conducting education on online platforms as of 16 March. Public local and intercity transportation began operating at 50% capacity on 24 March, and international flights were banned on 27 March. The first home lockdown period extended from 11–12 April 2020 for 30 metropolitan cities and Zonguldak for the weekend. The lockdown continued for the same cities from 18–19 April 2020. As of 23–26 April 2020, the home lockdown was applied throughout Turkey. Subsequently, a home lockdown was applied to all of Turkey again on 16–26 May 2020.

As a result of the pandemic, traffic mobility has changed; people's trust in public transportation has decreased, and the number of private vehicles has increased (Korkmaz, 2022). Additionally, the compulsory demand for online shopping due to the pandemic created a surge in the number of cargo and transportation vehicles in traffic. However, the lockdown measures applied to control the COVID-19 pandemic also had positive results (Aloi et al., 2020; Brodeur et al., 2021; Shilling & Waetjen, 2020), such as reduced traffic accidents (Christey et al., 2020; Nuñez et al., 2020; Oguzoglu, 2020; Saladié et al., 2020a). While 283,234 people were injured and 5,473 people lost their lives as a result of traffic accidents in Turkey in 2019, the number of people injured in traffic accidents decreased to 228,565 and the number of people who lost their lives decreased to 2,197 in 2020, when the pandemic bans started (Emniyet Genel Müdürlüğü [EGM], 2020; Türkiye İstatistik Kurumu [TUİK], 2020).

The interest in using statistical models to understand the traffic accidents that occur and to take the necessary precautions has grown, and many traffic accident prediction models using various methods have been described in the literature. These studies were carried out using statistical methods, and the speed of these studies has increased due to developments in the field of statistics and in computer programmes. Recently, these studies have used machine learning to make predictions about traffic accidents (Ma et al., 2019; Yavuz et al., 2021).

Machine learning is a category of algorithms that increase software programmes' ability to predict results accurately without explicit programming. In machine learning, algorithms can take input data and use statistical analysis to predict an output while updating the output as new data emerge (Envepo A.Ş., 2018). For example, Yavuz et al. (2021) made a classification of traffic accidents with fatalities and injuries in Antalya Province and its districts between 2012 and 2016 using the Naive Bayes (NB) machine learning method. Ma et al. (2019) carried out a spatial grid analysis of traffic accidents in Los Angeles with the Extreme Gradient Boost (XGBoost) algorithm and Geographical Information System (GIS), which are machine-learning methods. (Chong et al., 2005) proposed a new model using a combination of artificial neural networks (ANN) and regression trees

(RT) methods to estimate the degree of injury resulting from traffic accidents. Using the decision tree (DT) model, Chang and Wang (2006) concluded that the vehicle type is the most important variable affecting accident severity. Sohn and Shin (2001) determined the variables affecting the severity of traffic accidents in Korea using ANN, logistic regression analysis (LRA) and DT methods. Kwon et al. (2015) ranked the variables that cause traffic accidents according to their relative importance using NB and DT methods. Muhammed et al. (2017) tried to predict traffic accidents on highways using DT algorithms.

This study aims to conduct data-driven research using machine learning algorithms to analyse the impact of pandemic conditions on traffic accidents. The effects of changing traffic density and COVID-19 restriction policies on traffic accidents during the pandemic will be evaluated. In the study, the answers to the following main research questions were investigated. What are the differences between the number of traffic accidents before and during the pandemic? What are the most appropriate machine learning algorithms for analysing and predicting traffic accidents?

Therefore, within the scope of the hypotheses of the study, firstly, the effects of changes in traffic density on the number and type of traffic accidents during the pandemic period were investigated. Accordingly, the success of machine learning models in numerically predicting traffic accidents occurring during the pandemic period was examined to analyse the changes.

It is not known how the curfews imposed in Zonguldak province, and 30 metropolitan cities affect the number of traffic accidents. For this purpose, the number of fatal and injury traffic accidents occurring in Turkey between 2012-2019 was used and a prediction table was created with Python programming language on the Google Colab platform. Nonlinear regression analyses were performed using the XGBoost algorithm, which is a controlled machine learning algorithm in Python programming language. Tableau 2020.4 Desktop software was used to visualise the result values. The estimated number of accidents in 2020 was found and compared with the actual fatal and injury accident data from metropolitan cities and Zonguldak in 2020. Thus, the effect of COVID-19-induced curfews on the number of fatal and injury traffic accidents in 2020 was observed.

Using data from previous years, an answer to the hypothesis ‘How successful will machine learning models be in predicting the number of traffic accidents that may occur in the coming years?’ was sought. In addition, it has been investigated how changes in traffic density during the pandemic affect the number and type of traffic accidents.

2. Method

A retrospective number of fatal and injured accidents, number of people killed and injured, total number of vehicles and the population data for provinces in Turkey from 2012–2019 were taken from the reports of the Turkish Statistical Institute (TUİK, 2020). The data for 2020 were obtained from the annual report published by the Police Department (EGM, 2020).

2.1. Machine Learning

Statistical analysis in the study was carried out with machine learning, a sub-branch of artificial intelligence. With machine learning, a system that creates predictions by making inferences from the data using mathematical and statistical operations is created. Many different machine learning methods have emerged for this inference process. If the output of the method is categorical, then classification is performed. If the output is numerical, regression analysis is performed. Since the output of the present study was numerical, regression analysis was performed.

Machine learning has two different learning situations: unsupervised and supervised. The main purpose of unsupervised learning is training the system with algorithms to create a model or pattern from the available data. In unsupervised learning, examples of events and situations are known in advance, but the corresponding results (i.e., classifications) are not known in advance. In contrast, supervised learning predicts the result for future situations by using examples of past events whose inputs and outputs are discovered upon analysis. In the present study, previous data were investigated with multivariate regression analysis (the Supervised Machine Learning Method) using Python programming language on the Google Colab platform.

In supervised learning, regression analysis and linear and nonlinear algorithm types are available. In the current study, many linear and nonlinear regression analyses were performed to obtain the best estimation result. For the LRA, the following were applied: simple linear regression, ridge regression, lasso regression, elastic net regression, Bayesian linear regression and support vector regression (SVR) algorithms. For the non-linear regression analyses, gradient boosting regression, XGBoost regression, K-nearest neighbours' regression, AdaBoost regression, CatBoost regression and Light GBM regression algorithms were used as comparison metrics. The XGBoost algorithm provided the most significant results and is explained in detail below.

2.2. Python Libraries

In the Python programming language, libraries store the files belonging to the most-used code pieces. These libraries are stored in pre-written files that can be used repeatedly. The current study utilized Numpy, Pandas, MatPlotLib, SciKit-Learn, XGBoost, Light GBM and CatBoost libraries for the various algorithms mentioned above (Table 1).

Table 1. Libraries and algorithms used in the study's model

Names of Libraries	Algorithms
SciKit-Learn	Simple Linear Regression
SciKit-Learn	Ridge Regression
SciKit-Learn	Lasso Regression
SciKit-Learn	Elastic Net Regression
SciKit-Learn	Bayesian Linear Regression
SciKit-Learn	Support Vector Regression
SciKit-Learn	Gradient Boosting Regression
SciKit-Learn & XGBoost	XGBoost Regression
SciKit-Learn	K-Nearest Neighbours Regression
SciKit-Learn	AdaBoost Regression
CatBoost	CatBoost Regression
Light GBM & SciKit-Learn	Light GBM Regression

2.3. Comparison of The Used Algorithms

The above-mentioned algorithms were analysed to determine the algorithm with the best performance. The XGBoost algorithm had the best performance.

The evaluation of the algorithms considered the R-squared (R2), mean absolute error (MAE) and root mean square deviation (RMSE) values. These values are defined as follows:

- R2 *(coefficient of determination)* represents how well the values fit relative to the original values. The value of R2 varies between 0 and 1, and the closer it is to 1, the more meaningful it is (Deok, 2019). The values are interpreted as percentages, and the higher the value is, the better the model.

- MAE represents the difference between the original and predicted values and is subtracted by averaging the absolute difference over the dataset.

- RMSE is the error rate determined by the square root of the mean squared error (Deok, 2019).

Of these, lower MAE and RMSE values indicate a higher reliability of the analysis (Y. Lin & Li, 2020; Tang et al., 2020). The applied models are charted below in Table 2. As seen in the table, the algorithm that provided the best results for the metropolitan cities and Zonguldak Province was XGBoost.

Table 2. Comparison of algorithms used for metropolitan cities and Zonguldak Province

Algorithms	MAE	R^2	MSE	RMSE
Simple Linear Regression	846.42	0.88	1370630.30	1170.74
Ridge Regression	846.42	0.88	1370630.30	1170.74
Lasso Regression	846.42	0.88	1370630.30	1170.74
Elastic Net Regression	846.42	0.88	1370630.30	1170.74
Bayesian Linear Regression	845.96	0.88	1372605.33	1171.58
Support Vector Regression	945.66	0.43	6693012.49	2587.09
Gradient Boosting Regression	319.85	0.98	227619.54	477.09
XGBoost Regression	**289.41**	**0.99**	**146562.80**	**382.83**
K-Nearest Neighbours Regression	357.11	0.98	238257.71	488.12
AdaBoost Regression	410.46	0.98	272379.37	521.90
CatBoost Regression	311.39	0.98	187875.45	433.45
Light GBM Regression	518.33	0.94	696565.61	834.60

As seen in the Figure 1, using the XGBoost algorithm the measured and estimated numbers of fatalities and injuries for 2020 very similarly to one another overlaps.

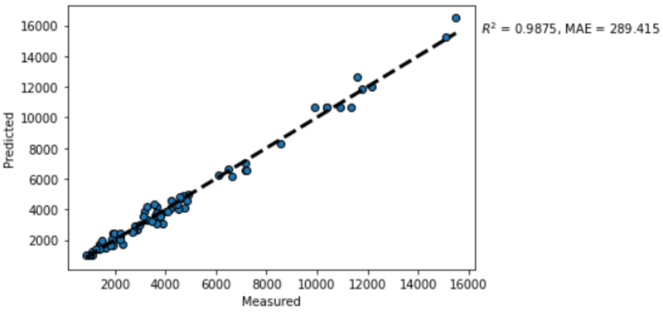

Figure 1. The measured and estimated numbers of fatalities and injuries for 2020 using the XGBoost algorithm

2.4. Extreme Gradient Boosting

XGBoost is a high-performance version of the Gradient Boosting algorithm that has been optimized with various arrangements. It can be used for regression and classification problems (Ibrahem Ahmed Osman et al., 2021). The following equations illustrate how XGBoost works in a dataset with m attributes and n samples (Dataset, [DS]), DS={(xa,ya) : a=1….n, xa ∈ Rm, ya∈R }).

Let $\hat{y}_a$ be the prediction data of an ensemble tree model produced from the following equations. K represents the number of trees in the model, as found by f_k (k-th tree).

$$\text{Å.}_a = \phi(x_a) + \sum_{k=1}^{K} f_k(x_a), \mathrm{f_k}) \in \mathcal{F} \quad (1)$$

To solve the above equation, the best set of functions must be determined by minimizing the losses and the arrangement objects, as follows:

$$L(\Phi) = \sum_a \mathrm{l}\,(y_a, \text{Å.}_a) + \sum_k \Omega\ (f_k) \quad (2)$$

In this equation, l represents the missing function, which is the difference between the actual data (y_a) and the predicted data ($\hat{y}_a$). Ω indicates that the model is quite confusing; this variable helps avoid overfitting the model. It is calculated by the formula below:

$$\Omega(f_k) = \gamma T + 0.5\lambda\, ||w||^2 \quad (3)$$

Here w is the weight of each leaf, and T is the number of leaves of the tree. DTs work by adding a new function f as the model continues its education. In this process, it is used to minimize the increase of this function in the training of the model. Therefore, in the tth iteration, a new tree is added, as follows:

$$L^t = \sum_{a=1}^{n} l\left(y_a\, \text{Å.}_a^{(t-1)} + f_t(x_a)\right) + \Omega(f_t) \quad (4)$$

$$L_{split} = 0.5 \left[\frac{(\sum_{a\in l_L} g_a)^2}{\sum_{a\in l_L} h_a + \lambda} + \frac{(\sum_{a\in l_R} g_a)^2}{\sum_{a\in l_R} h_a + \lambda} - \frac{(\sum_{a\in l} g_a)^2}{\sum_{a\in l} h_a + \lambda}\right] - \gamma \quad (5)$$

$$g_a = \partial_{\text{Å.}^{t-1}}\, \mathrm{l}\,(y_a, \text{Å.}^{(t-1)}) \quad (6)$$

$$g_a = \partial^2_{\text{Å.}^{t-1}}\, \mathrm{l}\,(y_a, \text{Å.}^{(t-1)}) \quad (7)$$

2.5. Model Parameters of XGboost

Several parameter values are needed to obtain the best model, and the parameter setting is particularly important for using multiple parameters for the XGBoost algorithm. XGBoost is used to prevent overfitting and prevents excessive complexity (Parsa et al., 2020). Overfitting occurs when the model is too complex (i.e., has too many features/variables compared to the number of observations). If the model has begun to memorize and work too hard on the dataset used for training, it will have very high prediction accuracy for the training data but will likely not be able to predict untrained or new data accurately (Bayraktutan & Özbilgin, 2013). Table 3 shows the parameters that were tested on the model with the XGBoost algorithm. Table 4 shows the best parameter values of the analysed model.

Table 3. Parameter values for the XGBoost algorithm

Parameters	Tried Parameter Values				
Learning rate	0.01	0.1	0.5	0.05	-
Max depth	5	8	10	10	15
Iterations	100	500	1000	1500	2000
Colsample by tree	1	0.5	0.1	-	-

Table 4. The best parameter values for the XGBoost algorithm

Parameters	The Best Parameter Values
Learning rate	0.01
Max depth	5
Number of iterations	500
Colsample by tree	1

3. Results

Due to the COVID-19 outbreak, lockdown restrictions were enforced in metropolitan cities and Zonguldak Province in Turkey in 2020. To determine the impact of the lockdown on fatality and injury traffic accidents in these cities, nonlinear multivariate regression analysis was compared to the results of other algorithms. The XGBoost algorithm, which provided the best results, was used, and the results were analysed. Of the data from 2012–2019, 25% were chosen randomly as test data, and the remaining 75% were chosen as training data. The data from Istanbul, which had much larger values than the data from other cities, were considered outlier. However, data cleaning was not performed to remove the Istanbul data from the model since cleaning of data was regarded as a limitation to the model.

3.1. Model Results of Metropolitan Cities and Zonguldak

Zonguldak and all metropolitan cities in Turkey were examined in the study as the first group. As seen in Table 5, the year, population, number of fatal and injury accidents, number of vehicles by provinces and number of accidents involving fatalities and injuries were predicted for 2020 with the XGBoost algorithm using the data from 2012–2019. Zonguldak was included in the same group as the metropolitan cities because lung diseases are common there due to the coal mining industry; therefore, the COVID-19 lockdown was imposed in Zonguldak as well as the metropolitan cities. Zonguldak province has very patients with chronic lung diseases. So, the management of COVID-19 in patients with chronic lung diseases requires a separate effort (Metintas, 2020). Therefore, Zonguldak was evaluated as metropolitan city and the provincial data from Zonguldak were also included in the study. In general, the accidents were fewer than predicted, except in two cities (Diyarbakır and Ordu). Thus, the lockdowns decreased the traffic accidents in most metropolitan cities. According to the predicted number of traffic accidents, the rate of decrease in metropolitan cities was 18.3%. Despite the decrease in metropolitan cities across Turkey, an increase was found in Diyarbakır and Ordu, which may have been due to quarantine restrictions not being employed strictly enough.

As seen in Figure 2, the actual data and predicted values were compared using the XGBoost algorithm. As seen in Figure 3 (created with Tableau 2020.4 Desktop program), the highest number of accidents was observed in Ankara, Izmir, Antalya, Bursa, Mersin and İstanbul. The population and number of vehicles in these cities are dense.

As seen in Figure 4, the relationship between population and the number of accidents involving fatal and injuries between 2012 and 2019 were observed. Population and severe accidents are directly proportional.

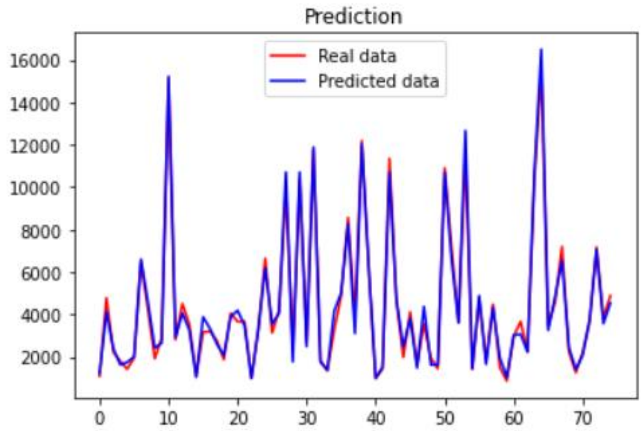

Figure 2. Comparison of the measured and predicted number of fatal and injury accidents in 2020

Figure 3. Average cases of accidents in metropolitan cities and Zonguldak

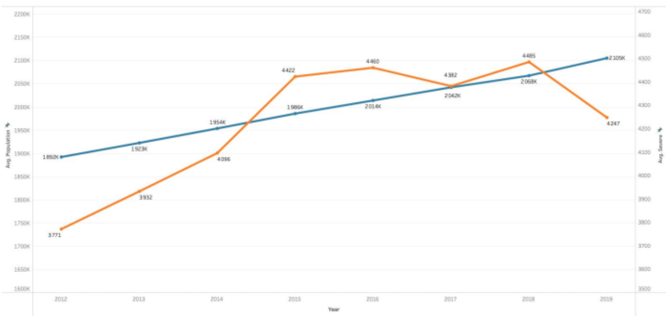

Figure 4. Population and the number of accidents involving fatal and injuries between 2012 and 2019

3.2. Normality Test Results

To evaluate the result of fatality and injury accidents in 2020, evaluating whether the difference between the predicted value and the actual value was statistically significant was important. First, a Shapiro Wilk test was performed as a normality test to determine whether the measurements had a normal distribution. P-values lower than 0.05 would indicate that the measurements did not have a normal distribution and that non-parametric tests should be applied, while p-values greater than 0.05 would show a normal distribution, in which case parametric tests should be applied (Bazlamit et al., 2020; Rezapour Mashhadi et al., 2017). The p-values were $p < .001$.

As they were quite smaller than 0.05 and the distribution was therefore not normal, non-parametric tests were employed. Thus, a Wilcoxon signed ranks test was performed. The predicted value and the actual value were compared to determine whether the difference obtained was significant. For the Wilcoxon signed ranks test statistic = 7, $p < .001$. In health sciences, if the p-value obtained as the result of this test is less than 0.001, the difference between the predicted and the actual number of accidents is regarded as statistically significant (Jayavel & Lizy, 2014). In social and physical sciences, significance is assumed when the p-value is less than 0.05 (Liu et al., 2019). As the p-value in this study was smaller than either of the criteria ($p < .001$), the difference between values was regarded as statistically significant.

One of the positive impacts of the measures implemented to control the spread of COVID-19 was the decrease in traffic accidents on both urban and interurban roads (Aloi et al., 2020; Brodeur et al., 2021; Shilling & Waetjen, 2020), which resulted in a marked fall in the number of traffic-related injuries and fatalities (Saladié et al., 2020). However, interestingly Lin et al. (2020) found that the number of non-fatal accidents decreased while the number of severe and fatal traffic accidents remained the same during the pandemic in two cities in the U.S., Los Angeles and New York City. Additionally, Qureshi et al. (2020) found a significant reduction in road traffic accidents resulting in minor or no injuries (M_{before}=14.5, vs. M_{after}=10.8, p < 0.0001) but not in accidents resulting in serious or fatal injuries (M_{before}=3.4 vs. M_{after}=3.7, p = 0.42) after mandated societal lockdown. The authors in both articles could not clarify the reasons behind lack of reduction in road traffic accidents resulting in serious or fatal injuries during the COVID-19 pandemic. Thus, as in other countries around the world, the COVID-19 pandemic led to a significant decrease in the number of fatal and injury traffic accidents in Turkey, especially in metropolitan cities where quarantine was enforced in 2020. Furthermore, this study showed that machine learning can make mistakes in extraordinary situations such as earthquake, war and pandemic, etc., no matter the accuracy of its predictions.

Table 5. Model results for metropolitan cities and Zonguldak

City	Year	Killed or Severely Injured Accidents	Population	Sum of Vehicles	Predicted Value	Percentage (%)
Adana	2020	4146	2258718	680645	6043.59	31.398
Ankara	2020	9572	5663322	2125454	12658.00	24.380
Antalya	2020	6901	2548308	1137476	8140.00	15.221
Aydın	2020	3103	1119084	474254	3684.82	15.790
Balıkesir	2020	3319	1240285	502080	4104.24	19.132
Bursa	2020	5405	3101833	945412	7365.61	26.618
Denizli	2020	2643	1040915	423574	3292.60	19.729
Diyarbakır	2020	2033	1783431	133568	1795.47	-13.229
Erzurum	2020	1083	758279	124761	1542.37	29.784
Eskişehir	2020	1838	888828	296918	2764.30	33.509
Gaziantep	2020	3231	2101157	539568	5643.75	42.751
Hatay	2020	3540	1659320	509371	3910.05	9.464
İstanbul	2020	15421	15462452	4565985	16737.00	7.863
İzmir	2020	8868	4394694	1487675	10703.00	17.145
Kahramanmaraş	2020	2215	1168163	243540	2713.28	18.364
Kayseri	2020	2954	1421455	390057	3537.43	16.493
Kocaeli	2020	3127	1997258	419821	3497.92	10.604
Konya	2020	4718	2250020	745076	5993.65	21.283
Malatya	2020	1459	806156	182560	1886.92	22.678
Manisa	2020	3608	1450616	610155	4594.24	21.467
Mardin	2020	966	854716	81820	1166.79	17.209
Mersin	2020	5085	1868757	640566	6096.63	16.593
Muğla	2020	3872	1000773	527163	4048.23	04.353
Ordu	2020	1618	761400	141047	1504.79	-7.523
Sakarya	2020	2166	1042649	299025	3253.17	33.419
Samsun	2020	2829	1356079	371919	3021.44	06.369
Şanlıurfa	2020	2806	2115256	269153	2981.42	05.884
Tekirdağ	2020	1870	1081065	280955	3177.05	41.140
Trabzon	2020	1491	811901	206640	1755.80	15.082
Van	2020	1145	1149342	82740	1397.82	18.087
Zonguldak	2020	875	591204	161323	1210.24	27.700

4. Discussion

The findings of this study reveal a significant decrease in the number of fatal and injury traffic accidents in Turkey during the COVID-19 pandemic, particularly in metropolitan cities where strict lockdown measures were enforced. These results align with previous studies conducted in various countries, which also reported a reduction in traffic accidents due to mobility restrictions and reduced vehicular traffic (Aloi et al., 2020; Brodeur et al., 2021; Shilling & Waetjen, 2020). For instance, Saladié et al. (2020b) found that mobility restrictions led to a sharp decline in road accidents and associated injuries in Spain, supporting the argument that limited movement directly correlates with fewer traffic incidents.

However, contrary to the overall trend of reduced accidents, an increase was observed in Diyarbakır and Ordu. This anomaly may be attributed to the inadequate enforcement of lockdown measures in these cities. Similar findings have been reported in other studies, where cities with less stringent quarantine policies experienced a lesser reduction in traffic accidents compared to regions with stricter measures (Qureshi et al., 2020). Furthermore, socio-economic and cultural factors may have played a role in shaping driver behaviors in these regions, necessitating further investigation into localized impacts of lockdown policies.

An interesting aspect of this study is the analysis of severe and fatal traffic accidents during the pandemic. While the overall number of accidents decreased, some studies indicate that the proportion of severe accidents remained stable or even increased. L. Lin et al. (2020) found that the number of non-fatal accidents decreased while the number of severe and fatal traffic accidents remained the same during the pandemic in two cities in the U.S., Los Angeles and New York City. A similar pattern was noted by Qureshi et al. (2020), who reported a reduction in minor accidents (M_{before}=14.5 vs. M_{after}=10.8, $p < 0.0001$) but found no significant change in fatal accidents (M_{before}=3.4 vs. M_{after}=3.7, $p = 0.42$) during the COVID-19 pandemic. These findings suggest that although there were fewer vehicles on the road, factors such as increased speeding on empty roads, riskier driving behaviors, and reduced law enforcement might have contributed to the unchanged fatality rates.

Moreover, the present study highlights the limitations of machine learning models in predicting outcomes during extraordinary circumstances such as pandemics, natural disasters, or war. Despite XGBoost providing highly accurate predictions under normal conditions, the unforeseen impact of lockdowns introduced inconsistencies between the predicted and actual accident rates. This observation aligns with the argument that machine learning models, despite their sophistication, can struggle to account for abrupt, unprecedented societal changes (Jayavel & Lizy, 2014; Liu et al., 2019). The results underscore the necessity of incorporating external factors, such as real-time government policies and human behavioral changes, to enhance predictive accuracy in such extraordinary scenarios.

This study has certain limitations that should be acknowledged. One key limitation is that the analysis is based solely on data from Türkiye, which may limit the applicability of the findings to other regions. Additionally, the study utilizes accident data from the period between 2012 and 2019, meaning that more recent trends and potential changes in accident patterns are not considered.

Overall, this study contributes to the growing body of literature examining the impact of the COVID-19 pandemic on road safety. It confirms the effectiveness of lockdown measures in reducing traffic accidents while also emphasizing the challenges in predicting accident patterns during global crises. Future research should focus on integrating adaptive machine learning models that can dynamically adjust to extraordinary events and investigate long-term trends in post-pandemic traffic behavior to develop more resilient traffic management policies.

Ethics Committee Approval Statement

Since the study was conducted with data obtained from secondary data sources, ethics committee approval is not required.

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Author Contributions

Percentages of the author(s) contributions is present below. All authors reviewed and approved final version of the manuscript.

	First author
C	100
D	100
S	-
DCP	-
DAI	-
L	100
W	100
CR	100
SR	100
PM	100
FA	100

Note. C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

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