UNIVERSIDAD DE EXTREMADURA

TESIS DOCTORAL

TÍTULO:

Avances en el conocimiento de la fragmentación de entornos protegidos causado por las carreteras y derivados de su diseño o de su exploración

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"En la vida no existe nada que temer, solo cosas que comprender"

Marie Curie

RESUMEN

Esta tesis doctoral aborda la afección al medioambiente de las carreteras desde el punto de vista de efecto barrera que producen en el medioambiente. El efecto barrera de una carretera puede ser entendido como la barrera física disruptiva que una infraestructura lineal ejerce sobre el territorio. Pero también, existen otros efectos derivados del uso de la infraestructura que imponen una barrera, no física, dividiendo, igualmente, ambos márgenes de la explanación de una carretera. Algunas de estas barreras no visibles son: la barrera acústica, producto del ruido del tráfico; o la barrera química, producto de los desechos ambientales que tanto los propios vehículos como los usuarios liberan al medio natural.

La investigación está contextualizada en la comunidad autónoma (CA) de Extremadura, España. Esta CCAA está compuesta por las dos provincias más extensas de España, Cáceres y Badajoz. A ello se añade una baja densidad de población en comparación con la densidad media en España o Europa. Extremadura tiene una densidad de población de 26,4 habitantes/km^2, frente a los 91,4 habitantes/km^2 de España o los 109 habitantes/km^2 de Europa. Estas características de tamaño y densidad de población hacen necesaria una red viaria extensa, que permita comunicar los municipios entre sí y a éstos con los núcleos de población principales y redes de transportes de primer orden. Por otro lado, las características de extensión y demografía citadas implican la existencia de una amplia proporción de espacios naturales y, como consecuencia, una parte significativa de la región está protegida por algún tipo de protección ambiental. De hecho, el 34% del territorio extremeño está protegido, frente al 27% en promedio en España o el 18% en la Unión Europea.

El grado de afección de la red de carreteras al medioambiente, en cuanto a la disrupción del territorio, ha sido evaluado mediante cuatro métricas de fragmentación. El estudio ha sido realizado sobre las unidades del paisaje de la

Red Natura 2000: las Zonas de Especial Protección de Aves (ZEPA) y las Zonas de Especial Conservación (ZEP). Las métricas empleadas en este estudio han sido Infrastructural Fragmentation Index (IFI), Urban Fragmentation Index (UFI), effective mesh size (Meff) y degree of landscape division (DIVI). A partir de los resultados obtenidos, se ha realizado un análisis para establecer la métrica más adecuada al estudio de fragmentación de hábitats a causa de las carreteras. Con ello, se pretende determinar la metodología más precisa para la gestión del territorio con relación a las actividades de gestión y conservación de las carreteras y el efecto barrera asociado a éstas.

Los cálculos de fragmentación de las unidades del paisaje han sido abordados a partir de parámetros geométricos producto de la interacción de las unidades del paisaje y las carreteras. En relación con las métricas empleadas en la comunidad científica se emplean dos formulaciones posibles para las métricas IFI y UFI. Dentro del estudio se han evaluado las dos formulaciones para cada métrica, estableciendo que las formulaciones propuestas para el IFI no pueden ser consideradas como equivalentes de modo que se propone la ecuación más adecuada al estudio. En cambio, las dos formulaciones propuestas para el UFI conducen a resultados que sí pueden ser considerados como estadísticamente equivalentes en un 80%. De la evaluación de las métricas empleadas, se obtiene que las métricas IFI, Meff y DIVI proporcionan resultados satisfactorios para la evaluación de fragmentación del paisaje a causa de las infraestructuras viales; aunque cada una de aquellas métricas resalta consecuencias diferentes de fragmentación. En cambio, la métrica UFI no ha mostrado resultados efectivos, ello queda explicado por los criterios de diseño de las unidades del paisaje.

Asociado a la fragmentación de hábitats producidas por las carreteras, el ruido generado por el tráfico puede ser considerado como una barrera física no visible. Esta afección, en lo relativo a sus efectos sobre los seres humanos, está ampliamente estudiada, estando demostrada la relación entre patologías de la salud y el ruido del tráfico. En el caso de afección del ruido del tráfico a la fauna silvestre existen estudios que evidencian la afección en determinadas especies de aves. El trabajo realizado ha analizado la relación entre el nivel de presión sonora generado por el ruido de tráfico y la temperatura del pavimento y ambiental, como uno de los parámetros que influye en el nivel de presión sonora generado y percibido en el entorno. Este efecto viene siendo estudiado por otros autores, fundamentalmente en experimentos basados en normas de referencia internacional. En este trabajo se consideró el estudio de la dependencia entre el ruido de rodadura y la temperatura ambiental en una carretera en condiciones normales de uso. Para ello se ha monitoreado la carretera N-521, empleando como fuente sonora el tráfico real de la carretera, con una IMD de 7.658 vehículos/día. La capa de rodadura del pavimento de la zona de experimentación es una mezcla bituminosa discontinua BBTM 11B de 3 cm de espesor, con un contenido en huecos mayor del 12% y con 7 años de antigüedad. Los resultados obtenidos en banda ancha mostraron una variación del nivel de ruido con la temperatura, con una relación de -0,058 ± 0,007 dBA/°C para la temperatura del pavimento y de -0,161 ± 0,020 dBA/°C para la temperatura del aire. Estos resultados ponen de manifiesto que el medio físico en el que se mide la temperatura parece ser importante.

Esta tesis doctoral está dentro del marco de investigación de dos proyectos competitivos de I+D+i desarrollados en colaboración entre la Universidad de Extremadura y empresas privadas. En lo relativo a la producción científica relacionada con este trabajo de investigación, han sido publicados dos artículos indexados en el Journal Citations Reports (JCR) y tres comunicaciones orales presentadas en congresos internacionales. La investigación realizada permite una continuidad en sus líneas de investigación. Por un lado, en relación con la evaluación de la fragmentación de hábitats, ya estamos trabajando en en la elaboración de nuevas métricas que permitan integrar diferentes aspectos recogidos de forma separada en las métricas actualmente existentes. En la línea de afección acústica medioambiental a causa del tráfico en carreteras, parten estudios comparativos en cuanto al efecto de las diferentes tipologías de pavimentos, secciones trasversales de la carretera, configuración de calzadas o carriles…; que pueden derivarse en implicaciones en relación con las normas de referencia para la evaluación, el cálculo y la medición del ruido de tráfico.

CAPÍTULO 1. INTRODUCCIÓN

1.1. Fragmentación de hábitats y métricas del paisaje

La fragmentación de hábitats es un concepto que puede ser abordado desde diferentes perspectivas que de, forma general, es evaluada mediante métricas. Existen métricas de fragmentación que combinan variables de diferente naturaleza, como es la huella humana, tipología de cultivos y otros factores antrópicos. Algunas de estas métricas son: HFI (Human footprint index), AVIRE (Average Value of the Infinitesimal Road Effect), CILIF (Composite Indicator of Landscape Fragmentation). Otras métricas emplean datos fundamentalmente geométricos ,producto de la intersección directa de un elemento o infraestructura en una unidad del paisaje (UP) de un medio natural.

Este estudio se centra sobre las carreteras como causa de fragmentación de las unidades del paisaje. Entre las métricas más empleadas en trabajos científicos de similar naturaleza está el IFI (Infrastructural Fragmentation Index), que combina datos fruto de la intersección geométrica de las infraestructuras lineales con las UP con datos característicos de las carreteras; UFI (Urban Fragmentation Index), que combina datos demográficos de las zonas urbanas con datos de la intersección geométrica entre ellas y las UP y Meff (effective mesh size) y DIVI (degree of landscape division) que emplean datos únicamente producto de la intersección geométrica de las infraestructuras y las UP.

En estudios de igual naturaleza, a escala europea, es la agencia de medio ambiente (The European Enviorement Agency) la encargada de evaluar la evolución de la fragmentación del paisaje en la Red Natura 2000 a causa de las carreteras en Europa; para ello emplea la métrica del Meff, (European Environment Agency (EEA), 2018).

El IFI es un indicador enfocado a evaluar la afección de las infraestructuras lineales en las unidades del paisaje. Su cálculo se basa en la geometría de las unidades del paisaje, en las partes que se generan por la fragmentación y en algunas características intrínsecas de las carreteras, como son el tipo de carretera o, en algunos casos, el tráfico que soporta. Empleando el UFI se evalúa la afección de los núcleos de población en las unidades del paisaje. Este índice se basa en la geometría de la UP, la geometría de la superficie de los cascos urbanos de los municipios y en algunas características intrínsecas de los núcleos urbanos, como es su población. El IFI y UFI son índices indirectamente relacionados, puesto que la existencia de núcleos urbanos obliga a la existencia de una red de infraestructuras lineales proporcional al número y tamaño de los núcleos que conecta. El Meff y DIVI, propuestos por Jaeger J., se basan únicamente en la geometría de la unidad del paisaje y de las partes en que se divide el paisaje por una cuestión o motivo determinado, (Jaeger, 2000).

De Montis et al. (De Montis et al., 2017) abordan la fragmentación del paisaje en zonas de especial conservación natural en España e Italia a través de las métricas IFI y UFI. En su trabajo se realiza una revisión de las diferentes métricas empleadas para los cálculos de fragmentación y se pone de manifiesto que tanto para el IFI como el UFI existen dos ecuaciones posibles de cálculo. En su trabajo Bruschi et al. (Bruschi et al., 2015), a través del IFI, estudian el nivel de fragmentación de los Parques Nacionales de Italia debido a las infraestructuras del transporte. El effective mesh size (Meff), el efective mesh density (Seff) y el Degree of landscape division (DIVI) son empleados por diferentes autores para evaluar la fragmentación a causa de las infraestructuras de áreas antrópicas, espacios naturales y ecosistemas (Buzzi et al., 2019; Canedoli et al., 2018; Cuervo & Møller, 2020; Freitas et al., 2012; Gounaridis et al., 2020; Hernández-Valencia et al., 2020; Jaeger et al., 2011; Li & Lin, 2019; Scholtz et al., 2018; Zomeni & Vogiatzakis, 2014). Lawrenceid et al., a partir del Meff y Seff estudia la fragmentación antropogénica a nivel global en las UP de las Red Natura 2000 en Europa, (Lawrenceid et al., 2021). Sus resultados reflejan, en diferentes puntos de

Europa, la existencia cambios poco significativos en relación a la fragmentación de UP protegidas por alguna figura de protección ambiental. Como resultado, evidencian diferencias en la evolución de los valores de fragmentación obtenidos en diferentes UP, estas diferencias tienen su origen en parámetros como la antigüedad del UP protegida, la orografía o el desarrollo de la región. Este trabajo está basado en un análisis preliminar de la European Environment Agency (EEA) que analiza de forma cualitativa la fragmentación de estos espacios naturales y sugiere que la fragmentación actual en los espacios protegidos en menor que en los no protegidos (European Environment Agency (EEA), 2018). De forma similar, Canedoli et al., analizan el grado de fragmentación de la Red Natura 2000 en Chipre empleando la métrica del Meff (Canedoli et al., 2017). Por otro lado, Zomeni and Vogiatzakis (Zomeni & Vogiatzakis, 2014), analizan, por medio de varios indicadores, el encaje de la Red Natura 2000 en Chipre, emplean el Seff como índice de fragmentación de hábitats. De forma general, la relación directa entre la Fragmentación del Paisaje (FP) y el decremento de la calidad en ecosistemas, disminución del número de individuos en una especie, desaparición de la misma, etc., es puesta de manifiesto en diferentes trabajos (Battisti, 2004; Battisti & Romano, 2007; Bruschi et al., 2015; Chen & Koprowski, 2016; De Montis et al., 2017; Wilcove et al., 1986).

Los trabajos citados abarcan la evaluación el efecto barrera de las infraestructuras únicamente desde el punto de vista de barrera física, no se considera de forma directa el efecto de contaminación ambiental o acústica que estas infraestructuras proyectan al medio natural y su influencia en los ecosistemas (Forman & Deblinger, 2000; Iglesias-Merchán et al., 2016; Rao & Koli, 2017; Summers et al., 2011). La FP causada por las carreteras no viene dada únicamente por la barrera física que imponen sobre el territorio, también influyen otros factores, como son el ruido que proyectan (Madadi et al., 2017) o el vertido de sustancias contaminantes al medio natural. El ruido dibuja una barrera invisible en el territorio que afecta la fauna que lo habita, en los trabajos (Boarman & Sazaki, 2006; Forman et al., 2002; Forman & Deblinger, 2000; Liu et al., 2008) se estudia el grado de afección de una carretera a diferentes sistemas naturales, contemplando el factor del ruido proyectado. Un estudio llevado a cabo en Madrid (Iglesias-Merchán et al., 2016) evidencia que determinadas especies de aves evitan anidar en lugares con un ruido mayor a Leq 40 dB. Otras consecuencias de la fase de explotación de una carretera: sal en la calzada, sustancias contaminantes acumuladas por la escorrentía, basura y materia orgánica o polvo disperso en el ambiente, acentúan el efecto barrera sobre el ecosistema, con efectos como la posible contaminación de los animales que habitan en el entorno; fuente de comida en calzadas, que a su vez atrae depredadores y que favorecen los atropellos y contaminación del medio vegetal aledaño (D'Amico et al., 2016).

1.2. Parámetros que influyen en la generación de ruido

El nivel sonoro que se genera en una carretera es un factor de contaminación que altera el medioambiente, actuando como un efecto barrera no visible originado por el uso de estas infraestructuras (Iglesias-Merchán et al., 2016; Meyer et al., 2019; Summers et al., 2011). El ruido generado por el tráfico rodado en las carreteras está condicionado por múltiples factores. Los factores que influyen en el nivel sonoro pueden clasificarse en, características de la propia infraestructura, características del tráfico y factores ambientales. Las características propias de la infraestructura son parámetros que pueden ser controlados en el proceso de diseño, modificación o conservación de la misma. Parte de estas características son la tipología del pavimento, el estado de conservación, el diseño de geometría en planta o alzado, etc. A diferencia de los factores asociados a la propia infraestructura, los asociados a las características del tráfico; por ejemplo, el flujo, la velocidad, la tipología de los vehículos, sus características intrínsecas o neumáticos que portan, son más complejas de controlar debido a la dificultad en el control de los usuarios para el acceso y uso de las infraestructuras. En cuanto los factores meteorológicos, afectan tanto a la propagación como a la generación de la energía sonora. Los aspectos relativos a la propagación se encuentran recogidos en las normas de referencia (ISO 1996-1, 2016; ISO 1996-2, 2017; ISO 9613-2, 1996a). Con relación a su influencia en la generación, su consideración en las normas de referencia es menor. En particular, la influencia de la temperatura en la generación de nivel de presión sonora es un fenómeno estudiado por los autores a nivel científico, aunque no recogido en las normas de referencia en la materia (ISO/PAS 11819-4, 2013; ISO/TS 11819-3, 2017; ISO/TS 13471-1, 2017; ISO 11819-1, 1997; ISO 11819-2, 2017; ISO 13325, 2019; ISO 1996-1, 2016; ISO 1996-2, 2017; ISO 9613-1, 1993; ISO 9613-2, 1996b, 1996a).

Las influencia de temperaturas del aire y del pavimento en la generación de nivel de presión sonora, son parámetros estudiados por diferentes autores (Anfosso-LédéE & Pichaud, 2007; Bueno et al., 2011; Bühlmann & Ziegler, 2011; Kneib et al., 2016; Liao et al., 2015; Yuan et al., 2019). Estos trabajos se desarrollan en base a normas de referencia para la caracterización acústica de un pavimento. Pocos estudios existen en los que, en condiciones normales de uso de una infraestructura de transporte por carretera, se estudie y compruebe el efecto de la temperatura sobre el nivel sonoro medido. Los análisis realizados estudian el efecto de la temperatura sobre el nivel de presión sonora generado en base a las variables tipologías de pavimentos, en función de la porosidad, tipología de neumático o vehículo y temperatura del aire, pavimento y/o neumáticos. De forma general, la relación existente entre el nivel de presión sonora y la temperatura del aire o calzada se lleva a cabo a través de relaciones lineales. Los coeficientes de variación hallados se encuentran entre -0.03 y -0.11 dBA/ºC. Además, algunos autores analizan también el efecto descrito en bandas de 1/3 de octava, con resultados que muestran comportamientos diferentes en función de la frecuencia (Anfosso-LédéE & Pichaud, 2007; Bueno et al., 2011; Bühlmann & Ziegler, 2011).

En (Anfosso-LédéE & Pichaud, 2007) se evalúa a través del método CPB, para una velocidad constante de 90 km/h, tres tipologías de pavimentos (denso, poroso y capa de rodadura de pequeño espesor), dos tipologías de neumáticos diferentes y un rango de temperatura de aire de 0 a 30 ºC y pavimento 0 a 50ºC. Como resultado, en relación a la temperatura del pavimento, obtienen un factor de influencia lineal de temperatura sobre nivel sonoro de -0.06 dBA/ºC en pavimentos cerrados con un coeficiente de determinación, R^2, de 0.74 y un factor de influencia para pavimentos porosos de -0.04 dBA/ºC y R^2 0.90. Resultados similares son obtenidos en (Bühlmann & Ziegler, 2011), en el cual se emplea el método CPX para la evaluación de tres tipos de pavimentos y dos tipos de neumáticos, en este caso el coeficiente de determinación obtenido es $R^2 = 0,8$ y los valores promedios de factor de influencia lineal de temperatura del aire sobre nivel sonoro en función del pavimento son, en pavimento cerrado, - 0.10 dBA/ºC, en pavimento poroso, - 0.08 dBA/ºC, y en pavimento de hormigón, - 0.07 dBA/ºC.

En (Bueno et al., 2011) se evalúa un pavimento de porosidad intermedia con un único neumático por el método de CPX y se obtiene un valor de influencia lineal de temperatura sobre nivel sonoro de -0.06 dBA/ºC, igual que el obtenido en (Anfosso-LédéE & Pichaud, 2007) para pavimento poroso. Se ha de tener en cuenta que el experimento realizado por (Bueno et al., 2011) tiene en cuenta la temperatura del pavimento, y el experimento de los autores (Bühlmann & Ziegler, 2011) se realiza a partir de datos de temperatura del aire.

De los resultados mostrados se observa que los valores obtenidos en (Liao et al., 2015) difieren de los obtenidos en (Anfosso-LédéE & Pichaud, 2007) y en (Bühlmann & Ziegler, 2011) destacar que los coeficientes de determinación obtenidos en son menores a los otros autores comparados (Tabla 1). En el caso de Liao et al., (Liao et al., 2015) los resultados obtenidos muestran valores para pavimentos cerrados, entre - 0.10 dBA/ºC y -0.05 dBA/ºC, para pavimentos porosos la diferencia es menor, entre -0.06 dBA/ºC y -0.08 dBA/ºC, es importante destacar que las velocidades de referencia cambian para los diferentes casos, éste puede ser un factor condicionante aunque los valores de R^2 obtenido por los autores explican una gran proporción de la variabilidad. En (Yuan et al., 2019) el estudio realizado evalúa el comportamiento acústico frente a la temperatura del pavimento de cuatro tipologías de pavimento por el método SPB para velocidades de circulación de 40 km/h, 60 km/h y 80km/h y dos tipologías de vehículos comerciales. De los resultados obtenidos en el trabajo se tiene que los coeficientes de influencia lineal de temperatura sobre nivel sonoro son muy similares para las tres velocidades expuestas, prácticamente idénticos en las dos tipologías de vehículos y están en el mismo orden de magnitud que los coeficientes obtenidos en (Anfosso-LédéE & Pichaud, 2007) y (Bühlmann & Ziegler, 2011). En este caso no se reflejan en el documento los valores de los coeficientes de determinación obtenidos. De forma general los métodos de medición empleados por los autores (Anfosso-LédéE & Pichaud, 2007; Bueno et al., 2011; Bühlmann & Ziegler, 2011; Liao et al., 2015; Yuan et al., 2019) evalúan el pavimento bajo condiciones controladas de tráfico y posible contaminación sonora a causa de otras fuentes.

Tabla 1. Parámetros y resultados de estudios de variación de nivel sonoro del ruido generado por tráfico rodado en una carretera con respecto a la variación de temperatura. Tipos de pavimentos, hormigones bituminosos: cerrado, intermedio, abierto y poroso ordenados de menor a mayor en función de nivel de porosidad y hormigones de cemento.

Work	**Tipología de Pavimento**	**Vel. de ref (km/h)**	**Neumático**	**Temp.**	**Método**	**Temp. ºC**	**ΔdBA/°C**	**R²**
(Anfosso-LédéE & Pichaud, 2007)	Cerrado	90	A	aire	CPB	0-30	-0.10	0.86
	Poroso	90	A				-0.06	0.85
	Thin film	90	A				-0.06	0.92
	Cerrado	90	B				-0.10	0.85
	Poroso	90	B				-0.06	0.92
	Thin film	90	B				-0.06	0.96
	Cerrado	90	-	Pav.		0-50	-0.06	0.74
	Poroso	90	-				-0.04	0.90
	Thin film	90	-				-0.04	0.86
(Bühlmann & Ziegler, 2011)	Cerrado	50 and 80	SRTT	aire	CPX	10-30	-0.10	0.8
	Concreto	50 and 80	SRTT				-0.08	
	Poroso	50 and 80	SRTT				-0.05	
	Cerrado	50 and 80	AVON AV4				-0.11	
	Concreto	50 and 80	AVON AV4				-0.06	
	Poroso	50 and 80	AVON AV4				-0.08	
(Bueno et al., 2011)	Intermedio	50	Pirelli P6000	Pav.	CPX	15-50	-0.06	--
(Liao et al., 2015)	Cerrado	70		aire	OBSI	5 -30	-0.05	0.28
	Abierto	70					-0.09	0.37
	SMA (asfaltos de masilla de piedra	70					-0.11	0.62
	Poroso	70					-0.08	0.74
(Yuan et al., 2019)	Cerrado	40	Vehichles Pajero® 2003 and Passat® 2008	Pav.	SPB	5-22	-0.09	--
	Intermedio						-0.08	--
	Abierto						-0.08	--
	Poroso						-0.04	--
	Cerrado	60					-0.09	--
	Intermedio						-0.08	--
	Abierto						-0.07	--
	Poroso						-0.04	--
	Cerrado	80					-0.09	--
	Intermedio						-0.08	--
	Abierto						-0.07	--
	Poroso		Pajero				-0.03	--

En la Tabla 1 se muestra un resumen de los parámetros empleados, métodos de evaluación y resultados obtenido en los trabajos realizados por los autores (Anfosso-LédéE & Pichaud, 2007; Bueno et al., 2011; Bühlmann & Ziegler, 2011; Liao et al., 2015; Yuan et al., 2019). En general, se observa que los valores obtenidos en los diferentes trabajos son similares entre sí para condiciones de medición comparables. La revisión realizada abarca, en gran medida, las tipologías de pavimentos estándar existentes y configuraciones de velocidad y tipología de neumático. Estos experimentos son realizados para condiciones de tráfico controladas, vehículos y neumáticos concretos y métodos de medición específicos diseñados para la evaluación concreta del ruido neumático-carretera.

El análisis de resultados en el espectro de frecuencias en bandas de 1/3 de octava que realizan los autores (Anfosso-LédéE & Pichaud, 2007; Bueno et al., 2011; Bühlmann & Ziegler, 2011), muestra, de forma general, la existencia de una relación lineal del nivel sonoro frente a la temperatura, con coeficientes negativos y una mayor relación en alta y baja frecuencia; entendiéndose por baja frecuencia (31,5 Hz a 630 Hz), media frecuencia (800 Hz a 1250 Hz) y alta frecuencia (1,6 kHz a 5 kHz). En los resultados mostrados en (Anfosso-LédéE & Pichaud, 2007) se observa que la temperatura afecta a la generación de nivel de presión sonora con mayor magnitud en la franja de baja frecuencia, de 125 Hz a 500 Hz y de alta frecuencia,1,6 kHz a 5 kHz. Los resultados mostrados en (Anfosso-LédéE & Pichaud, 2007) muestran una tendencia de disminución del nivel sonoro con respecto al aumento de temperatura de forma general, no obstante, en el análisis en bandas de 1/3 de octava entre 125Hz y 315 Hz se evidencia que aumento de 21 ºC a 26 ºC produce un aumento del nivel sonoro registrado en estas frecuencias. En (Bühlmann & Ziegler, 2011) el análisis en frecuencias refleja que el nivel sonoro es inversamente proporcional a la temperatura en las frecuencias de 1/3 de octava. El criterio de calidad establecido en el trabajo de Bülhmann and Ziegler, estudiado mediante regresión lineal, es Std. error ≤ 0.2 dBA o R2 ≥ 0.9, (Bühlmann & Ziegler, 2011). Los resultados obtenidos se consideran explicativos en el rango completo de frecuencias de 1/3 de octava. Los valores hallados difieren en función de la tipología de neumático y del material y porosidad de calzada. Los resultados con mejores explicaciones de la variabilidad han sido hallados en media frecuencia (800 Hz a 1250 Hz).

El comportamiento, en banda de 1/3 de octava, de la relación del nivel sonoro con la temperatura es analizado en las frecuencias de 200 Hz a 16 kHz (Bueno et al., 2011). De forma global, encuentran una relación de temperatura y nivel sonoro inversamente proporcional para una relación lineal entre estos parámetros. Las frecuencias de 200 Hz y 250 Hz muestran un coeficiente de variación del nivel sonoro con la temperatura próximo a cero (< -0,02), mientras que el valor de mayor magnitud (≈ - 0,10) se registra en la frecuencia de 2 kHz. Los autores no muestran el coeficiente de correlación obtenido. En este trabajo el valor para banda ancha del coeficiente de variación lineal del nivel sonoro con respecto a la temperatura es de -0.06 (Bueno et al., 2011).

Las normas ISO son un referente en cuanto a calidad para la ejecución de un experimento. En materia de ruido, para el diseño y ejecución del proceso de realización de las medidas de esta tesis doctoral han sido empleadas como referencia las normas ISO (ISO/PAS 11819-4, 2013; ISO 11819-1, 1997; ISO 1996-1, 2016; ISO 1996-2, 2017). La norma (ISO 1996-1, 2016) establece los criterios de medición para día, tarde y noche y contempla las diferencias existentes entre los diferentes medias de transporte (carretera, ferrocarril, aéreo) y ruido industrial. La parte 2 de la norma ISO 1996, (ISO 1996-2, 2017) establece los parámetros a controlar para el estudio del nivel de presión sonora según sea el ruido en carreteras, ferrocarril, vehículos aéreos o ruido industrial. Quedan establecidos en esta norma los requerimientos técnicos de los equipos de medida necesarios para garantizar la calidad del experimento. En cuanto al ruido en carreteras, se dan criterios generales que permiten establecer el número de vehículos que dan un resultado de nivel de potencia preciso o el mínimo de tiempo establecido para una medición, se establecen los parámetros meteorológicos a controlar en el experimento (velocidad y dirección del viento, humedad relativa y temperatura) y se indica la posición del sonómetro con respecto a la fuente en función de la configuración del entorno y del tipo de fuente. De forma específica y aplicable a este trabajo, se pueden extraer las siguientes recomendaciones, (ISO 1996-2, 2017): se recomiendan equipos de medida clase 1 (CEI 61672-1); se hace la advertencia que más allá de 50ºC, temperatura del equipo, se puede aumentar la incertidumbre de medición; se hace la recomendación de calibrar antes y después de una medida; respecto al tiempo de medida, 10 minutos se expresa como tiempo suficiente para las características del caso de estudio y se indica la necesidad de medir y registrar los valores de las variables meteorológicas velocidad y dirección del viento, humedad relativa y temperatura y la ubicación del equipo de medida.

En cuanto a la relación entre temperatura y nivel de potencia sonora, la norma (ISO 1996-2, 2017) no establece ningún criterio de corrección. Pero se cita la norma ISO 9613-1 (ISO 9613-1, 1993) como referencia para el cálculo de la atenuación del nivel sonoro en su propagación en situaciones exteriores dados los condicionantes atmosféricos. Se cita en la norma la necesidad de recabar datos de temperatura en el inicio y fin de la medición. Naturalmente, la temperatura a medir indicada en la norma será la del aire, al evaluar con ella los efectos de las condiciones atmosféricas sobre la propagación del sonido.

Las normas (ISO/PAS 11819-4, 2013; ISO 11819-1, 1997), establecen los parámetros y pautas particulares para evaluación acústica del ruido neumático/carretera para dos experimentos concretos. (ISO 11819-1, 1997) establece el método de evaluación de la influencia del tipo de superficie de calzada en el nivel de presión sonoro registrado por el método estadístico de paso de vehículos (Statistical Pass-By method, (SPB). Esta norma está dirigida a clasificar las propiedades acústicas de la superficie de calzada mediante el índice SPBI empleando el control del nivel de presión sonora registrado para el paso de un vehículo determinado. Para ello se establecen, de forma general, los parámetros necesarios de calidad del experimento, que son similares a los establecidos en (ISO 1996-1, 2016; ISO 1996-2, 2017). Los criterios más relevantes son, posición de equipos de medida, categoría de estos y condiciones de campo libre, geometría en planta y alzado del tramo de vía ensayado, registro de condicionantes meteorológicos, clasificación del tipo de carretera en función de velocidad de circulación, número de carriles y calzadas y clasificación del tráfico en función de la tipología de vehículos. En cuanto a la temperatura, se indica la necesidad de recabar datos de temperatura del aire y calzada con equipos de 1ºC de precisión. No existen en la norma indicaciones de las posibles correcciones de nivel de presión sonora en función de la variación de la temperatura (ISO 11819-1, 1997). La parte 4 de la ISO 11819 (ISO/PAS 11819-4, 2013) establece una variación para el análisis del tráfico mediante el método SPB (ISO 11819-1, 1997) empleando una tabla de respaldo, este documento no propone un método o fórmula para la corrección del nivel de presión sonora medido en función de la temperatura.

Dentro del marco de normas ISO desarrolladas para la clasificación del tipo de superficie colocado en una calzada de una carretera en función del comportamiento acústico, existen dos métodos más (ISO/TS 11819-3, 2017; ISO 11819-2, 2017), no relacionados con la naturaleza del ensayo realizado. A continuación, van a ser analizados con el fin de conocer la existencia de posibles propuestas de correcciones del nivel de presión sonora con respecto a la temperatura. En (ISO 11819-2, 2017) se establecen los parámetros para la clasificación del tipo de pavimento en base a sus características acústicas mediante la metodología close-proximity (CPX), esta norma señala la necesidad de disponer de lecturas de temperatura del aire o pavimento, establece que ambas son proporcionales a excepción de casos con excesiva vegetación o grandes edificios, cuyo efecto lo extrae de (Sandberg et al., 2008). En la norma no se establecen las pautas o fórmulas posibles para la corrección del nivel de presión sonora en función de la temperatura, (ISO 11819-2, 2017). La norma ISO (ISO/TS 11819-3, 2017) es un complemento de la norma (ISO 11819-2, 2017) y establece los parámetros de neumáticos de referencia para la realización del experimento. Por último, la norma (ISO 13325, 2019), cuyo fin es evaluar la emisión de ruido en función del tipo de neumático, también ha sido revisado con el fin de conocer las posibles correcciones de nivel en función de temperatura establecidas. Esta norma no define dicha corrección, además la propia norma indica que no debe ser tenida en cuenta para evaluar el ruido del tráfico en carreteras.

CAPÍTULO 2. MARCO DE ESTUDIO

2.1. Marco geográfico y ambiental

La Comunidad Autónoma de Extremadura, formada por las dos provincias más extensas de España, Cáceres y Badajoz, se ubica en la franja centro-oeste de la Península Ibérica. Posee una extensión superior a 41.600 km^2 y puede ser asemejada a un rectángulo, con lados este-oeste de 170 km y norte-sur de 250 km. La Figura 1 ubica la región de estudio en el contexto de Europa.

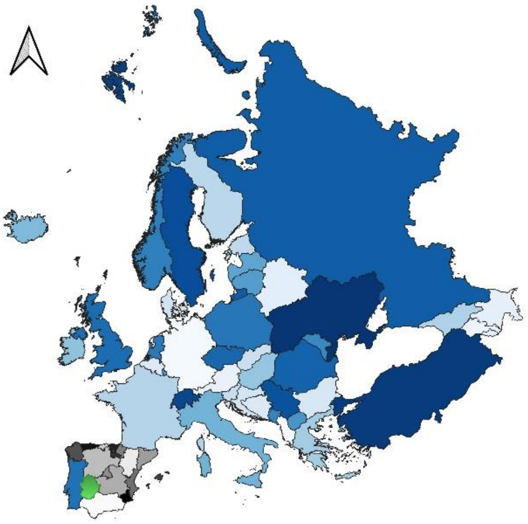


Figura 1 Contextualización espacial del área de estudio. Gama de azules Europa, gama de grises CCAA de España y en verde Extremadura.

En relación con la orografía del territorio estudiado y su relevancia para el diseño y construcción de la infraestructura viaria, la geografía de Extremadura se compone, de forma dominante, por penillanura como forma característica de paisajes suaves y alomados. La penillanura ocupa prácticamente dos tercios de la extensión de la provincia de Cáceres, en la que se encajan los barrancos del río Tajo. En Badajoz llega, por el sureste, hasta la depresión del Guadiana y, una vez superada, ocupa casi todo sureste de la provincia, con las grandes extensiones de la Siberia y La Serena, (Rosado, 2015). A partir de los datos del proyecto europeo CORINE Land Cover 2018, se clasifican las tipologías del paisaje en cincho clases: superficies artificiales, zonas agrícolas, zonas forestales con vegetación natural y espacios abiertos, zonas húmedas y superficies de agua. En la Tabla 2 se presentan, para Extremadura, las proporciones de las superficies en función de la clasificación indicada. Los datos aportados evidencian la escasa representación de los suelos artificiales (urbanos e industriales), frente a los agrícolas y forestales, (CLC, 2018), (Tabla 2).

Tabla 2. Superficies de usos del suelo en porcentaje, Comunidad Autónoma de Extremadura (España) (CLC, 2018).

Uso del suelo	**CLC 2018**
Superficies artificiales	0,99%
Zonas agrícolas	61,92%
Zonas forestales con vegetación natural y espacios abiertos	35,37%
Superficie de agua	1,72 %

En la Tabla 2, puede observarse que el dominio del paisaje son zonas agrícolas (61,92% de superficie total de la región), siendo significativo también la superficie zonas forestales con vegetación y espacios abiertos (35,37%).

La densidad poblacional de Extremadura es de 26,4 hab/km^2, frente los 91,4 hab/km^2 promedio de España o los 109 hab/km^2 promedio de Europa (Eurostast, 2019). La región cuenta con 165 municipios en la provincia de Badajoz y 223 en la provincia de Cáceres. En la Figura 2 se muestra la distribución de municipios según el número de habitantes. Se observa una forma de pirámide invertida en la que un 31,44 % de los municipios tienen menos de 500 habitantes y tan solo un 9 % de municipios tienen más de 5.000 habitantes (Instituto Nacional de Estadística, 2020).

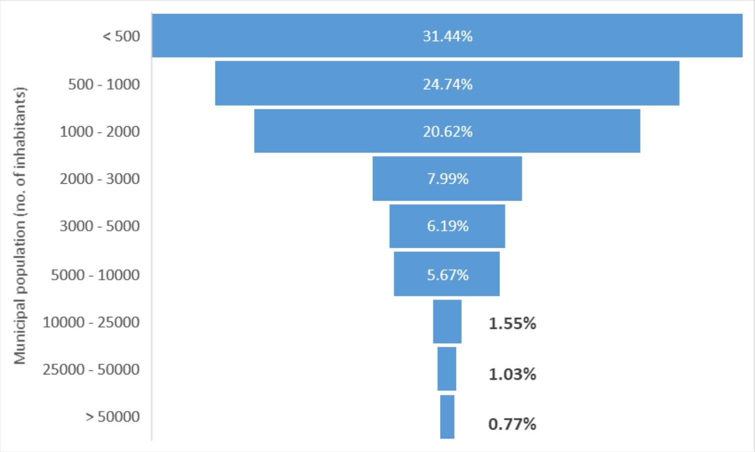


Figura 2. Estadística de distribución de municipios por población en Extremadura (España). Fuente de los datos (Instituto Nacional de Estadística, 2020).

El número de municipios existentes, distribuidos en la elevada superficie de la región, tiene como consecuencia directa una muy amplia red de carreteras que debe conectarlos. La red de carreteras, con un total de 9.105 km, se estructura en vías de distinta categoría según la capacidad de tráfico que soporta y el tamaño de las poblaciones conectadas: Red de carreteras del estado, con 21 vías y 1.593 km de longitud; Red de carreteras autonómicas, con 104 vías y 3.794 km de longitud y Red de carreteras locales, con 402 vías y 3.718 km de longitud.

La calidad paisajística de un territorio es un valor complejo y subjetivo de cuantificar, (Battisti, 2004; De Montis et al., 2018; Gómez Orea & Gómez Villarino, 2013; Ministerio de Agricultura Alimentación y Medio Ambiente, 2013b, 2013a). En Extremadura, el número y extensión de las unidades del paisaje que conforman la Red Natura 2000 existente es un indicativo del compromiso institucional para la conservación de hábitats. La RN2000 (European Union, 1992) determina dos tipologías de protección, zonas especiales de protección de aves (ZEPA) y zonas de especial conservación (ZEC) (European Union, 1992). Las ZEPA son definidas en el año 1995 y recientemente actualizadas en diciembre de 2020 (European Union, 1997, 2009). Estas unidades del paisaje han de "preservar, mantener o restablecer una diversidad y una superficie suficiente de hábitat para todas las especies de aves" (European Union, 1992). Existen unidades del paisaje con otras figuras de protección ambiental que buscan la preservación de hábitats con premisas similares a la RN2000. En este grupo deben considerarse las siguientes: Lugar de Importancia Comunitaria (LIC), Reserva de la Biosfera, zonas RAMSAR y Parques Naturales, Nacionales o Internacionales. En la actualidad, un 34% del territorio de Extremadura está protegido con alguna de las figuras de protección ambiental citadas anteriormente. Dentro de éstas, la Red Natura 2000 (ZEPA y ZEC) supone la mayor superficie protegida, existiendo 71 unidades del paisaje con protección ZEPA, con una superficie total de 11.016 km^2, y 89 unidades del paisaje con protección ZEC, con una superficie total de 9.332 km^2. Considerando, de forma independiente, la superficie dedicada a cada tipo de figura de protección ambiental, los Parques Nacionales suponen un 0,43 % del total del territorio, los Parques Naturales un 0,87 %, las Zonas Especiales de Protección de Aves (ZEPA) un 26,15%, las Zonas de Especial Conservación un 22,40 % y los Espacios Naturales Reserva de la Biosfera un 9.04 %. En Extremadura, tanto el número de zonas bajo estas otras figuras de protección, como la superficie involucrada, es muy inferior al que integra la RN2000. Además, una parte de la superficie incluida en estas LU ya se encontraba protegida como ZEPA o ZEC. Por tanto, el trabajo realizado se centra el análisis individual de la RN2000. También es importante tener en cuenta que, a menudo, una misma unidad del paisaje se encuentra protegida por las dos figuras de protección que contempla la Red Natura 2000 (ZEPA y ZEC). En otros casos, una LU con protección de ZEC está contenida en una LU de mayor superficie con protección de ZEPA o viceversa. Es por ello que el resultado de fragmentación de las unidades del paisaje con protección de ZEPA y ZEC puede ser similar en determinados casos.

En la Figura 3 se muestra la distribución de ZEC y ZEPA en función de la superficie. Se observa que un 34 % de las LU con protección de ZEPA tienen una superficie mayor de 10.000 Ha y el 61% abarca una superficie mayor de 200 Ha. En el caso de las ZEC, es el 18% de las LU las que disponen de una superficie mayor de 10.000 Ha y el 73 % mayor de 200 Ha. La superficie es un factor clave en el diseño de las unidades del paisaje. Por un lado, cada especie animal o vegetal requiere de un espacio mínimo en su hábitat. Por otro lado, a mayor superficie abarcada mayor fragmentación es posible que exista debido a la dispersión de los núcleos de población y a las carreteras que permiten acceder a ellos; ya que las carreteras suelen buscar el camino más corto para conectar dos puntos.

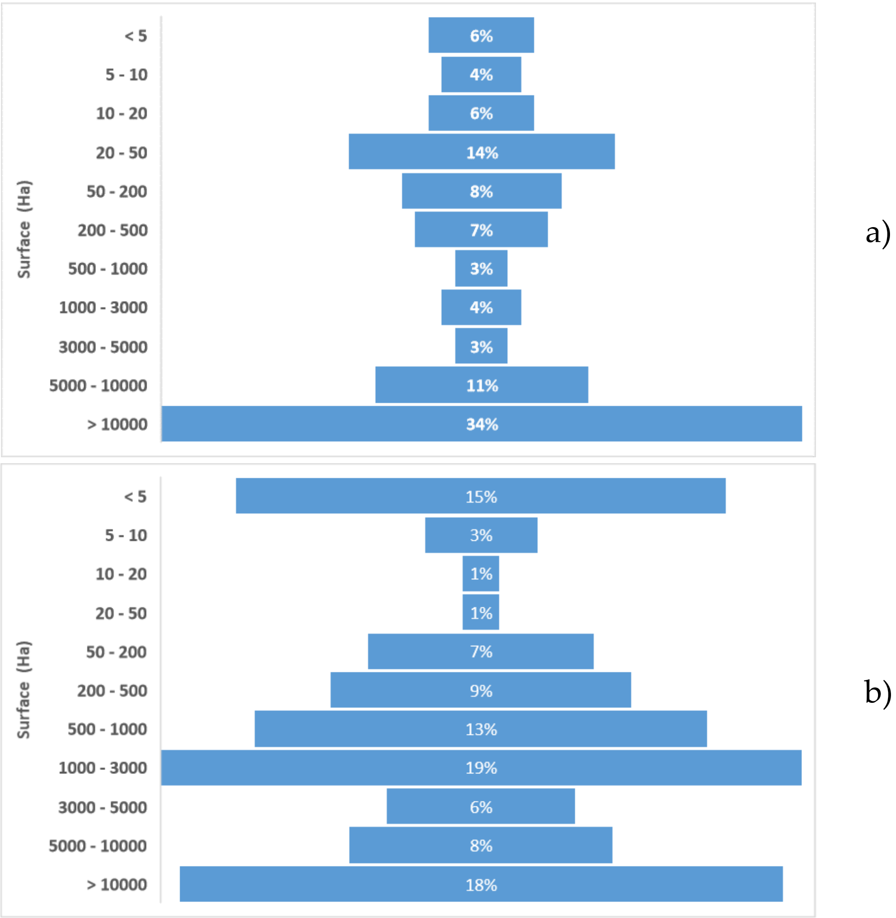
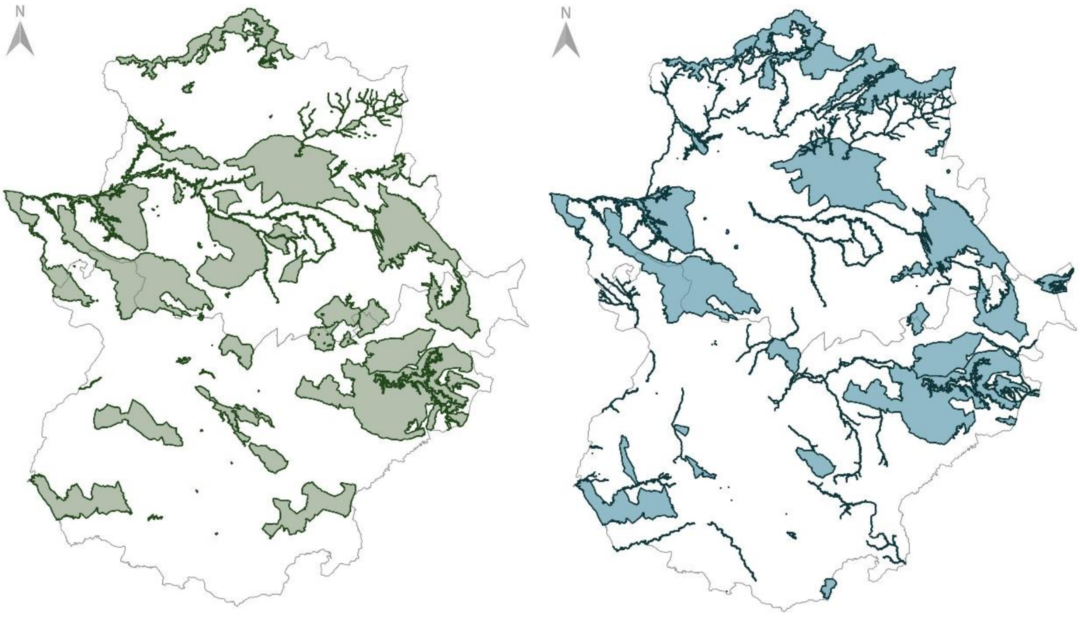


Figura 3. Estadística de superficie de figuras de protección de la Red Natura 2000 en Extremadura (España). a) ZEPA; b) ZEC

La Figura 4 muestra el encaje de zonas ambientales protegidas en la región de Extremadura. Las áreas protegidas están distribuidas en toda la región, siendo la franja noroeste en la que mayor densidad de espacios protegidos existe. Esta zona se ubica en la frontera con Portugal. En lo relativo a su orografía, es una zona montañosa, con ríos y en lo referente a su demografía. Además, es una de las zonas con menor densidad de población de España: ocupando, en el año 2019, el puesto tercero de 19 unidades administrativas y de la Unión Europea el puesto 26 de 746 unidades administrativas (Eurostast, 2019). La gestión de la red de carreteras de una región implica decisiones que pueden afectar a su condición geométrica y, por tanto, a la fragmentación directa del territorio.



a) b)

Figura 4. Distribución espacial de áreas protegidas de la Red Natura 2000 en Extremadura. a) ZEPA; b) ZEC. Fuente de los datos (MITECO, 2021).

2.2. Situación actual de las carreteras de Extremadura

Para el análisis de la situación actual de las carreteras en Extremadura se ha partido de la documentación cartográfica existente, mediante el empleo de diversas fuentes (Gobierno de España, 2020a, 2020b). A partir de ellas se han elaborado, mediante el software de información geográfica QGIS, diferentes mapas (Figura 5, Figura 6 y Figura 7) (*QGIS. GIS Application That Is Built on Top of and Proud to Be Itself Free and Open Source Software (FOSS).*, 2021). Estos mapas muestran las carreteras existentes en la región clasificadas según su categoría administrativa. La Figura 5 contiene la totalidad de las carreteras de Extremadura y la Figura 6, a) y b), muestra parcialmente las redes para una mejor visualización y comprensión de su estructura.

La clasificación de las carreteras se realiza según su categoría administrativa, por lo que tenemos que se puede diferenciar entre: Vías Nacionales; Vías Regionales; Vías Provinciales; Vías locales y comarcales.

Las vías nacionales son las de mayor capacidad de tráfico. Éstas, por regla general, tienen como características principales largos recorridos que conectan comunidades autónomas y grandes afluencias de tráfico. Dentro de esta categoría administrativa se puede distinguir entre carreteras, que son vías de calzada única y doble sentido de circulación de forma general, y autovías, vías de doble calzada y doble sentido de circulación. No obstante, en los casos en que ha sido construida una autovía con el mismo itinerario que una carretera nacional, ésta ha visto minorado significativamente el caudal de tráfico que soportaba.

Las carreteras nacionales son vías que, por regla general, disponen de un ancho de calzada de, al menos, 7-8 metros y arcenes de, al menos, 1 a 2,5 metros; lo que supone un ancho de plataforma de 9 a 12 metros. La geometría en planta y alzado se separa del terreno buscando la seguridad y comodidad para los usuarios de la vía, lo que se supone una barrera disruptiva en el territorio. Las autovías presentan aún mayores diferencias de nivel con el terreno natural y mayores anchos de plataforma, contando con, al menos, una configuración de dos calzadas con dos carriles por calzada, separadas por una mediana. Ello hace de las autovías una barrera física poco franqueable trasversalmente.

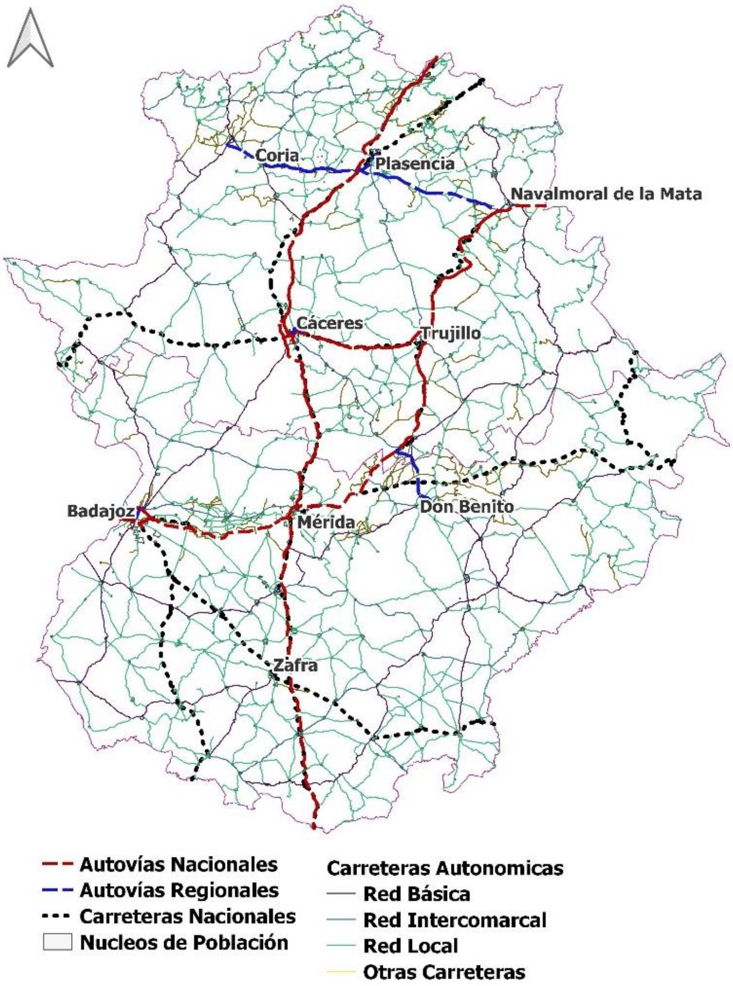
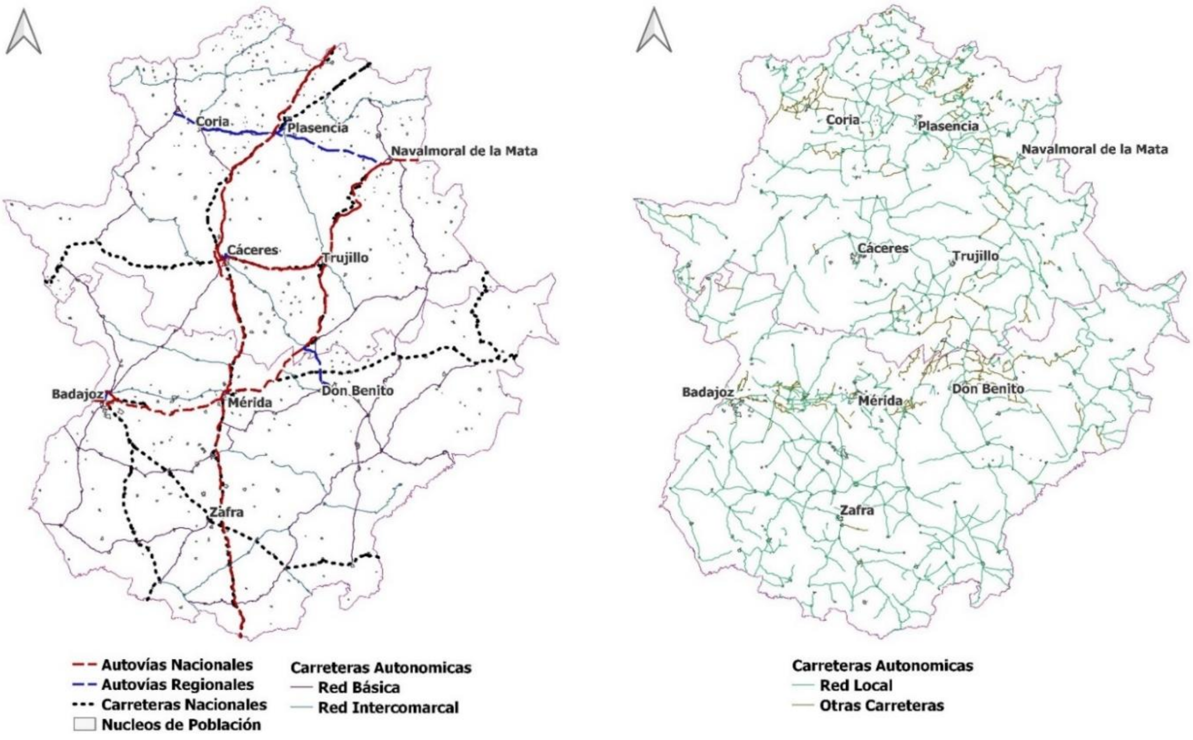


Figura 5. Situación actual de las carreteras de Extremadura.

Dentro de las carreteras regionales de la Junta de Extremadura también puede diferenciarse entre autovías y carreteras secundarias. La proporción de autovías es considerablemente menor a la de carreteras y son autovías que conectan grandes municipios con vías de comunicación rápidas, como es la EX–A2, que conecta la zona de Vegas Altas del Guadiana con la autovía A-5. O son autovías que conectan zonas de la región con vías de comunicación rápidas, como es la EX–A1, que conecta el noroeste de la región con las autovías A-66 y A-5. Las carreteras regionales se encuentran clasificadas administrativamente de mayor a menor orden. La categoría se encuentra, de forma general, directamente relacionada con las características técnicas de la carretera y la capacidad de tráfico que soporta. Se pueden distinguir:

- Red básica (Figura 6 a). Presentan recorridos interprovinciales. Esta categoría posee características geométricas que buscan la seguridad y comodidad del usuario, con anchos de carril de 3,5 metros y anchos de arcén de 0,5 a 1 metro. La geometría en planta y alzado hace que, en menor medida que las carreteras nacionales, se genere un efecto disruptivo del territorio.
- Red Intercomarcal (Figura 6 a). Está constituida por carreteras de menor recorrido, cuya pretensión es la unión de comarcas. Esta tipología de carreteras presenta características técnicas de menor nivel a las anteriores, con anchos de carriles de 3 a 3,5 metros y arcenes de 0 a 0,5 metros. La carga de tráfico de estas carreteras, de forma general, es menor a las anteriores; existiendo casos en que, por necesidades de tráfico, estas carreteras, de forma parcial o total, han sido actualizadas, mejorando sus características geométricas. De forma general, se encuentran más integradas en el territorio, por lo que su efecto disruptivo es menor.
- Red Local (Figura 6 b). Dentro de la red local de carreteras se encuentran las que poseen recorridos más cortos. Estas carreteras conectan municipios entre sí o con municipios con redes de circulación de mayor capacidad. Estas redes presentan una baja carga de tráfico y menores características técnicas que las anteriores, con anchos de carril de 3 metros y de forma general sin arcén o arcenes de ancho inferior a 0,40 metros. El trazado en planta y en alzado está adaptado al terreno por lo que el efecto disruptivo es bajo.



a) b)

Figura 6. Clasificación de las carreteras de Extremadura.

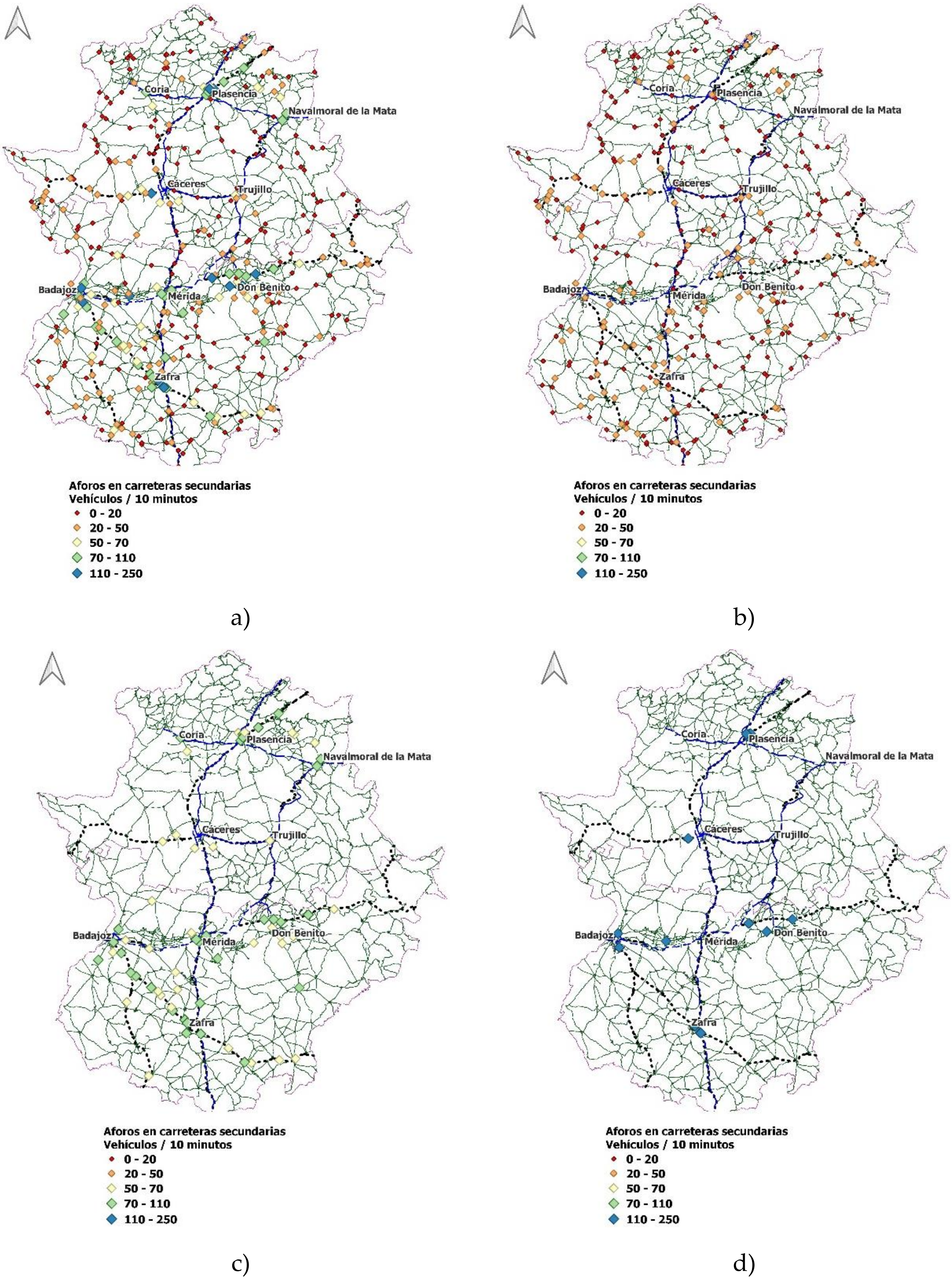
La Re de Carreteras en Extremadura se completa con otras carreteras que son, bien propiedad de la diputación provincial, bien propiedad de los municipios o mancomunidades. Éstas son carreteras con características similares a la red local, con pequeñas cargas de tráfico y características geométricas dirigidas a adaptarse al terreno existente y evitar grandes disrupciones en el territorio (Figura 6 b).

Se observa, en la Figura 6 a, que la de red de vías nacionales y regionales de los dos primeros niveles (red básica e intercomarcal) estructuran el territorio, unen los grandes municipios y áreas, pero no se observa gran densificación de estas vías en el territorio. Son las vías regionales, de la red local y el resto de vías (Figura 6 b) las que presentan, a simple vista, una mayor densidad. Como se ha indicado, estas vías son las que menor impacto proyectan al medio ambiente, ya que su geometría se adapta al terreno por el que discurren y las cargas de tráfico que soportan son bajas.

2.3. Situación actual del tráfico en las carreteras

El trabajo presentado propone realizar una evaluación de los parámetros de generación de potencia sonora en una carretera en base al ruido del contacto neumático-carretera producido por un flujo de vehículos en condición de servicio de la carretera. Para ello es necesario de disponer de un número de vehículos que permita promediar los efectos sonoros inducidos por la morfología del vehículo, tipología de neumático y velocidad del tráfico, principalmente. La norma UNE-EN ISO 11819-1 (ISO 11819-1, 1997) recomienda la suma de una serie de vehículos, según ligeros o pesados, dentro de esta suma se recomiendan al menos 100 vehículos ligeros. Además, se requiere de la disposición para medir una zona horizontal, de forma que los vehículos circulen sin forzar la aceleración del vehículo ni frenar y con una sección trasversal horizontal de la carretera con el terreno natural (sin desmonte ni terraplén).

En la Figura 7 se muestran los resultados de los aforos de las carreteras de calzada única de la CCAA de Extremadura. Se incluyen los datos de aforos de las carreteras del Estado y de las carreteras de la Junta de Extremadura. La clasificación de los aforos está expresada en vehículos cada 10 minutos, entendiendo que un intervalo de 10 minutos es adecuado para la observación de los efectos incluidos en la generación de ruido del tráfico rodado. Este intervalo permite medir garantizando cierta estabilidad meteorológica durante la medida. Sobre todo, con variaciones en la temperatura aceptables para el objetivo perseguido en el estudio. Para la obtención de la IMD cada 10 minutos se ha dividido la IMD proporcionada por las administraciones entre 12 horas de servicio "funcional" de la carretera y entre 6 para obtener el resultado cada 10 minutos.



a) b) c) d)

Figura 7 Aforo de las carreteras de calzada única en Extremadura.

La Figura 7 muestra los resultados de aforos IMD cada 10 minutos correspondiente a un sexto de la duodécima parte de la IMD registrada por la estación aforadora. La Figura 7 a) muestra todos los aforos de las carreteras de calzada única en Extremadura. La Figura 7 b), c) y d) muestra, únicamente, parte de los aforos, en función del flujo total estimado para 10 minutos. Para los estudios en materia de acústica planteados sería necesario partir, al menos, de un aforo estimado en el rango de 110 a 250 vehículos (Figura 7 d)). El rango de 70 a 110 vehículos ((Figura 7 c)) también puede ser de utilidad para la ejecución de los ensayos planteados; ya que, si se ubican las horas de mayor caudal de vehículos, es posible obtener el número de vehículos mínimos requeridos en los trabajos.

En la Figura 7 d) se observa que existe un aforo con una flujo total estimado para 10 minutos en 110 a 250 vehículos, ubicado en la N-521, próxima a la Ciudad de Cáceres, en el tramo que va de Cáceres al municipio de Malpartida de Cáceres. Dada la cercanía al centro de trabajo, se propone este punto de medida de cara a poder aprovechar en mayor grado el horario de medición. Con el fin corroborar que este dato se cumple se han realizado diversos aforos manuales de vehículos en emplazamiento de aforos.

CAPÍTULO 3. FRAGMENTACIÓN DE LA RED NATURA 2000 EN EXTREMADURA A CAUSA DE LAS INFRAESTRUCTURAS VIALES

Sánchez-Fernández, M., Barrigón Morillas, J. M., Montes González, D., & de Sanjosé Blasco, J. J. (2022). Impact of Roads on Environmental Protected Areas: Analysis and Comparison of Metrics for Assessing Habitat Fragmentation. Land, 11(10), 1843.

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Article

Impact of Roads on Environmental Protected Areas: Analysis and Comparison of Metrics for Assessing Habitat Fragmentation

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Abstract: The present study focuses on evaluating the effect of fragmentation caused by road infrastructures on a territory with singular characteristics such as low population density and a high proportion of its surface area protected by the Natura 2000 network. Based on the IFI, UFI, $\mathrm{M_{eff}}$ and DIVI metrics, the state of fragmentation of the landscape units (LU) was studied from two different approaches, considering two different protection figures, and the degree of suitability of the metrics used for the objective pursued was analysed. The results show that the expressions proposed for the indicators which measure the fragmentation of landscape units (LU) originated by road infrastructures (IFI, M_{eff} and DIVI) assess different causes and consequences in the territory than that proposed for fragmentation originated by urban areas (UFI). The combination of all indicators allows for the identification of shortcomings and strengths of the LU analysed and, consequently, evaluation of the effectiveness of the design of the LU and need for improvement. The outcomes of fragmentation analysis of the LU in the area under study varied depending on the criterion applied and the protection figure considered. A general increasing trend for all indicators was found in terms of the number of LU units and LU surface as the level of fragmentation rises. The results of this study are useful for decision-making on territory and road infrastructures management and new approaches to the organisation of the Natura 2000 network.

Keywords: road infrastructures; Natura 2000 network; protected natural areas; environmental management; landscape fragmentation metrics; landscape unit

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1. Introduction

The road infrastructure network is one of the main causes of fragmentation of natural habitats in which wildlife thrive [1–3]. Through the European Landscape Convention (ELC), organisations such as the European Union reflect nowadays the importance of the conservation of natural environments [4–6]. At the scientific level, authors evaluate equations and situations in which landscape fragmentation may constitute a risk to the natural environment. Battisti C. et al. reviewed the number of scientific investigations on the subject in recent decades and the approaches of the works on the basis of the keywords used [7].

This study assessed the state of fragmentation caused by road infrastructure in landscape units belonging to the Natura 2000 network in the Extremadura region (Spain). This is an area with low population density and a large dispersion of municipalities, which is classified in the European administrative category NUTS-3. The effect of roads was evaluated through the specific indicators Infrastructural Fragmentation Index (IFI), effective mesh size ($\mathrm{M_{eff}}$) and the degree of landscape division (DIVI) and, indirectly, through the Urban Fragmentation Index (UFI) indicator, which measures the fragmentation caused by urban areas.

The road network has historically offered a service to society adjusted to the demands of each period and conditioned to the existing technical and economic capacities. At the beginning of the road network development, this double dependence meant that these infrastructures had to be built in accordance with the topography of each territory. This implied that the construction works did not significantly transform the terrain's profile, but rather adapted to it [2,3,8]. Technological advances and the needs and demands of society lead to the construction of more disruptive roads that can involve the formation of physical barriers in the territory through which they run [9–12].

The European Directives 97/49/EC and 92/43/EEC introduce strategic guidelines for nature conservation in the framework of the European Union [13,14]. The need for preservation and recovery of the natural environment becomes widespread in the institutional and social spheres, becoming a global concern. The European Union established the Natura 2000 network (RN2000) in 1992, which aims to protect flora and fauna and to preserve and improve natural habitats through the designation of Protected Areas (PA) [14,15] . The European Environment Agency is in charge of assessing landscape fragmentation and its trend in Europe in order to know the evolution of fragmentation in the Natura 2000 network in recent years [16].

The extent to which any infrastructure impacts on the natural habitat is complex to determine [2,3,12,17–19]. This topic is approached by different authors from a social and environmental point of view in a general or particular way for specific infrastructures in order to evaluate the intrinsic effect of the infrastructures [17–23]. Different landscape fragmentation metrics have been proposed for this purpose, which are used by different researchers depending on the case study. Indicators such as the IFI and the UFI are employed for the assessment of landscape fragmentation [24–28]. While the IFI is focused on evaluating the effect of linear infrastructures on landscape units (LU), based on the geometry of the LU, the portions generated by fragmentation and the intrinsic characteristics of roads, the UFI assesses the effect of population settlements on these landscape units. This index is based on the geometry of the LU and the surface of the urban areas of municipalities. The IFI and the UFI are indirectly related indices since the existence of urban areas requires the existence of a network of linear infrastructures proportional to the number and size of the towns they connect. Other indicators of landscape fragmentation, such as the $\mathrm{M_{eff}}$, the effective mesh density (S_{eff}) and the DIVI, proposed by Jaeger J. [29,30], are only based on the geometry of the LU and of the parts into which the landscape is divided. They are also used by different researchers to determine landscape fragmentation [31–37]. The authors Schmiedel. and Culmsee used the $\mathrm{M_{eff}}$to estimate the fragmentation of natural areas, combining different sources of fragmentation for the calculation of the metric, in order to evaluate the vegetation richness of the studied area [31]. The M_{eff} is also applied by the European Environment Agency to analyse the effectiveness of protection versus the fragmentation of the Natura 2000 network [16].

De Montis et al. [24] addressed landscape fragmentation in natural areas of special conservation in Spain and Italy through the IFI and the UFI. A review of the different metrics used for fragmentation calculations was conducted and it was found that two possible calculation equations exist for both the IFI and the UFI. Bruschi et al. [28] studied the level of fragmentation of Italian National Parks due to transport infrastructures through the IFI. The M_{eff}, the S_{eff} and the DIVI are used by different authors to assess the fragmentation caused by infrastructure of anthropic areas, natural spaces and ecosystems [34–40]. Based on M_{eff} and S_{eff}, Lawrenceid et al. [6] studied anthropogenic landscape fragmentation in the LU of the Natura 2000 network in Europe. The results reflect, in different areas in Europe, the existence of insignificant changes in terms of fragmentation in the LU covered by some type of environmental protection, according to the criteria established in their research. In addition, differences in the evolution of fragmentation are evidenced according to the age of the protected LU, orography or development of the region. This study is based on a preliminary analysis of the European Environment Agency (EEA) that qualitatively analyses the fragmentation of these natural areas and suggests that fragmentation in protected areas is lower than in unprotected areas, [16]. Almenar, J. B. et al. analysed the evolution of habitats in Luxembourg as a support tool for territorial planning [31]. Similarly, Schmiedel and Culmsee used fragmentation metrics in local forest management policy, assessing the appropriate minimum plot size in forests and estimating the social impact and response of citizens [31]. The direct relationship between landscape fragmentation (LF) and the decrease in the quality of ecosystems, the reduction in the number of individuals of a species and disappearance of species have been highlighted in different publications [24,28,41–44].

2. Materials and Methods

2.1. Landscape Metrics

The infrastructural fragmentation index (IFI) makes it possible to study the interaction between the territory and linear infrastructures. Two expressions were suggested for its calculation in the scientific literature. Di Ludovico and Romano [45] proposed Equation (1) for the analysis of habitat fragmentation due to roads, while La Rovere et al. [46] studied the concept of infrastructure fragmentation density using Equation (2).

$$\mathrm{IFI} = \frac{\left(\sum_{i=1}^{i=n} \mathrm{L_i} * \mathrm{O_i}\right) * \mathrm{N} * \mathrm{Pt}}{\mathrm{At}} \tag{1}$$

$$\mathrm{IFI} = \frac{\left(\sum_{i=1}^{i=n} \mathrm{L_i} * \mathrm{O_i}\right)}{\mathrm{St}} \tag{2}$$

where $\mathrm{L_i}$ is the length of the section of linear infrastructure contained in the evaluated landscape unit; $\mathrm{O_i}$ is a dimensionless occlusion coefficient between 0 and 1, which represents the degree of disruption that the linear infrastructure exerts on the territory; N is the number of parts into which the evaluated landscape unit has been divided; Pt is the total perimeter of the evaluated landscape unit; At is the total area of the evaluated landscape unit and St is the reference surface. The index i corresponds to the different infrastructures present in the analysed area and n is the total number of infrastructures.

Equations (1) and (2) are similar, but there are two differences. Firstly, there is the term $N * Pt$, which has increasing values as the areas become more fragmented. Secondly, there is the denominator which, in Equation (1), is the total area of the assessed landscape unit, while in Equation (2) it is a reference area; therefore, equal for the different assessed landscape units.

The variables in Equation (1) are objective, except for the O_i coefficient, which depends on the subjectivity with which it is valued. Romano and Tamburini proposed a method for calculating the coefficient based on road traffic flow $O_i = \frac{n}{60}$, where n is the number of vehicles per day using the road [47]. On the other hand, Biondini et al. [48] suggested values of O_i as a function of the intrinsic importance based on the typology of linear infrastructure: $O_i = 1$ for highways, $O_i = 0.5$ for roads with a high expected traffic load (national and regional roads), and $O_i = 0.3$ for local roads. All these values have been used by different researchers [24–26,28,46]. Ledda and De Montis [25] evaluated the influence of the occlusion coefficient for the calculation of the IFI, reaching the conclusion that the IFI seems to be sensitive to the variation of O_i according to a progressive and linear trend.

Another disruptive effect on the territory, not contemplated in the IFI, is the influence of urban settlements located within an environmental area. The use of natural resources and the development of economic or recreational activities affect the natural habitat within a certain radius of influence. This is indirectly related to the existence and use of infrastructures. Furthermore, the dispersion of small urban agglomerations favours the multiplication of local roads, while the concentration of large urban centres limits the number of roads but increases the importance of their impact. The Urban Fragmentation Index (UFI) assesses the fragmentation of the territory regarding the urban settlements it contains. De Montis et al. [24] examined the relationship between the IFI and UFI indices in 6 landscape units (LU). They found some relationship between the indices but concluded that 6 LU are not enough to define a statistically significant relationship between the two fragmentation indicators. In this work, the UFI is used as another fragmentation indicator that can reinforce the IFI values obtained. From the review of indices carried out by De Monties et al. [24], Equations (3) and (4) are extracted as possible formulas for the calculation of the UFI:

$$\mathrm{UFI} = \frac{\frac{\sum_{i=1}^{i=n} S_i}{A_t} * \sum_{i=1}^{i=n} p_i}{\sqrt[2]{\pi * \sum_{i=1}^{i=n} S_i}} \tag{3}$$

$$\mathrm{UFI} = \frac{\left(\sum_{i=1}^{i=n} p_i * S_i * o_i\right)}{A_t} \tag{4}$$

where S_i is the surface area of the urban settlement; p_i is the perimeter of the urban settlement; A_t is the total area of the landscape unit; o_i is the dimensionless occlusion coefficient established according to the permeability of the urban settlement or its neighbourhood. The index i corresponds to the different urban settlements present in the area analysed and n is the total number of urban settlements.

As is the case of the IFI, o_i is a subjective variable. Romano and Tamburini [47] proposed, for the study of fragmentation of large landscape units in Italy due to the growth of urban agglomerations, values of o_i according to the nature of the urban area (industrial 100%, business district 80%, intensive residential areas 60%, and extensive residential areas 40%). This classification was subsequently used by other authors for studies of territorial fragmentation due to urban areas [24,26,48] although the classification of urban settlements in one of these classes is complex.

The M_{eff} is an indicator that allows studying the effective parcel size of a LU fragmented by both linear infrastructures from a purely geometric point of view and by surface elements [29,30]. This indicator is not affected by the existence of small area patches and, in the case that all patches have the same size, the effective mesh size would be that area. In this sense, a higher M_{eff} value represents a lower landscape fragmentation and vice versa. The measurement unit of M_{eff} will be that considered for the areas in the calculation using Equation (5):

$$M_{eff} = \frac{\sum_{i=1}^{n}\left(A_i{}^2\right)}{A_t}\left(\mathrm{km}^2\right) \tag{5}$$

where A_t is the total area of the landscape unit and A_i is the area of the fragmented surface. The index i corresponds to the different surfaces into which the area analysed has been divided due to the linear infrastructures and n is the total number of parts.

From the M_{eff}, two other metrics are derived: the effective mesh density (S_{eff}) and the degree of coherence C or DIVI [29]. The S_{eff} represents the occupancy of the M_{eff} (expressed as a percentage of one) in relation to an established surface area, which some authors set as 1 km^2 [30]. Since the S_{eff} can be interpreted as the inverse of M_{eff}, it has not been considered as a metric in the results section. The DIVI or C can be understood as the probability that two individuals can be found in a given environmental area. It is the representation of the M_{eff} in the LU area expressed as a percentage of one. Values close to 0 represent highly fragmented areas and those close to 1 indicate non-fragmented areas [26,30].

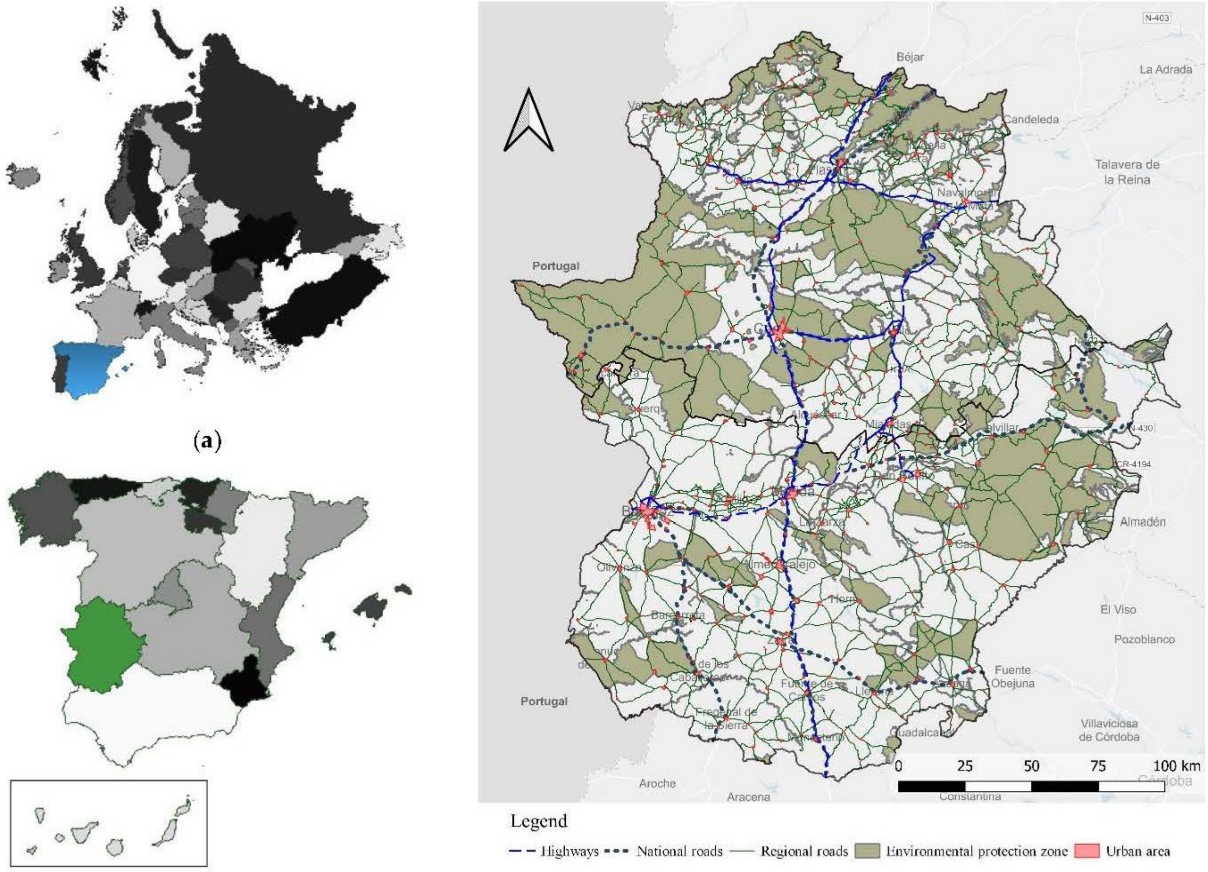
$$S_{\mathrm{eff}} = \frac{1}{M_{\mathrm{eff}}} \tag{6}$$

$$\mathrm{DIVI} = C = \frac{M_{\mathrm{eff}}}{A_t} = \sum_{i=1}^{n} \left(\frac{A_i}{A_t}\right)^2 \tag{7}$$

where M_{eff} is the effective mesh size; A_t is the total area of the landscape unit; A_i is the area of each of the fragmented surfaces. The index i corresponds to the different surfaces into which the area analysed has been divided due to the linear infrastructures and n is the total number of parts.

2.2. Territory, Demography and Landscape Units

The region of Extremadura is made up of the two largest provinces in Spain, Cáceres and Badajoz. It is located in the central-western strip of the Iberian Peninsula, with an extension of more than 41,600 km^2 and resembles a rectangle with east–west sides of 170 km and north–south sides of 250 km (Figure 1). It ranks as the sixth region in Spain in terms of the highest number of protected landscape units and the sixth region in Spain in terms of the highest percentage of protected area. In terms of area, Spain has 27% of its territory protected, above the European Union average of 18%. Figure 1 places the study area in the context of Europe and shows all the environmental zones with all the protection typology of the Extremadura region superimposed on roads and urban settlements.



(a)

(b)

(c)

Figure 1. Spatial contextualisation of the study area. (**a**) Location of Spain (in blue) in Europe; (**b**) location of Extremadura (in green) in Spain; (**c**) map of Extremadura with communication routes and urban and environmental protected areas.

The population density of Extremadura is 26.4 inhabitants/km², while the averages in Spain and Europe are 91.4 and 109 inhabitants/km², respectively [49]. The region has 165 municipalities in the province of Badajoz and 223 in the province of Cáceres. Figure 2 shows the distribution of municipalities according to the number of inhabitants. An inverted pyramid can be observed in which 31.44% of municipalities have less than 500 inhabitants and only 9% of municipalities have more than 5000 inhabitants [50]. An extensive road network is necessary to connect all these municipalities distributed over the large surface area of the region, with a total length of 9105 km. This network is divided into distinct categories according to the traffic capacity and the size of the municipalities connected: state road network, with 21 roads and 1593 km; regional road network, with 104 roads and 3794 km; and local road network, with 402 roads and 3718 km.

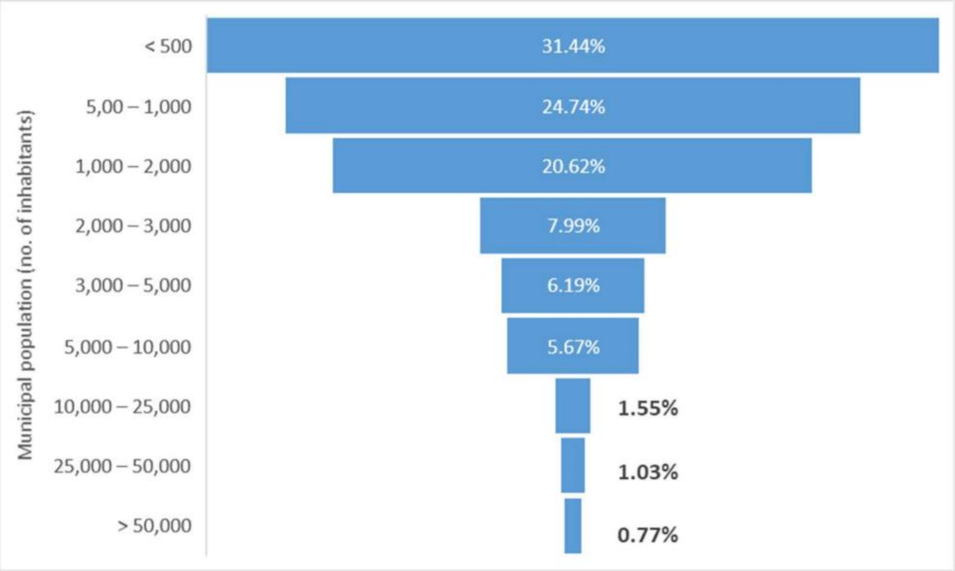


Figure 2. Distribution of municipalities by population in Extremadura (Spain) [50].

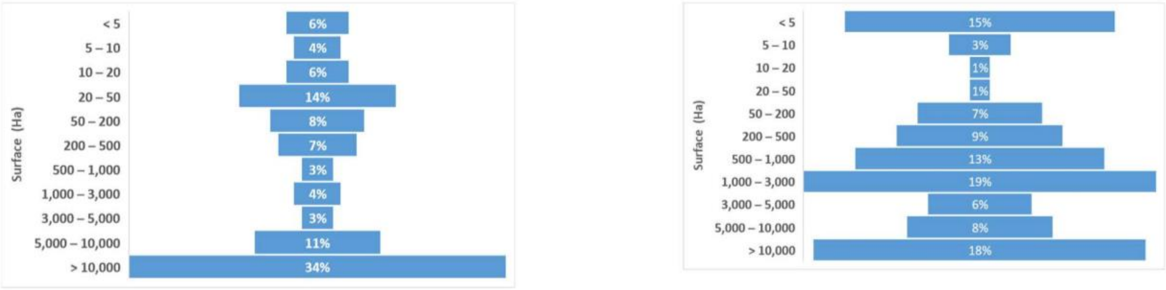
In relation to the orography of the territory studied and its relevance for the design and construction of the road infrastructures, the geography of Extremadura is predominantly made up of peneplains as a characteristic form of smooth and not very abrupt landscapes. Based on data from the European CORINE Land Cover 2018 project [51], landscape typologies are classified into five classes: artificial surfaces, agricultural areas, forest areas with natural vegetation and open spaces, wetlands and water bodies. Table 1 shows the proportions of surfaces in Extremadura according to the above classification. Data show that artificial land (urban and industrial) is under-represented in comparison with agricultural and forestry areas. Table 1 shows the representation of land uses extracted from the information of [51]. It is observed that the two largest fractions of land use in Extremadura are mostly agricultural areas (62%) and forest and seminatural areas (35%), with a minority of artificial surfaces (1%).

Table 1. Land use areas in Extremadura (Spain) [51].

Land Use	CLC 2018
Artificial surfaces	0.99%
Agricultural areas	61.92%
Forest and seminatural areas	35.37%
Wetlands	0.00%
Water bodies	1.72 %

The Natura 2000 network [14] determines two typologies of protection as Special Bird Protection Areas (SPAs) and Special Areas of Conservation (SACs) [14]. SPAs were defined in 1995 and recently updated in 2009 [13,52]. This line of protection is aimed to "preserve, maintain or re-establish a sufficient diversity and area of habitat for all bird species" [52]. There are landscape units with other figures of environmental protection that seek the preservation of habitats with similar premises to the Natura 2000 network. The following should be considered in this group: site of community importance (SCI), biosphere reserve, RAMSAR areas and natural, national or international parks [14,53,54]. The number and extent of the landscape units in Extremadura that are part of the existing Natura 2000 network is an indication of the institutional commitment to habitat conservation. At present, 34% of Extremadura territory is protected by one of the abovementioned environmental protection types. Of these, the Natura 2000 network (SPAs and SACs) represents the largest protected area with 71 landscape units of SPA protection (11,016 km^2) and 89 landscape units of SAC protection (9332 km^2). Considering each type of environmental protection figure independently, national parks constitute 0.43% of the total area, natural parks 0.87 %, Special Bird Protection Areas (SPAs) 26.15%, Special Areas of Conservation (SACs) 22.40% and biosphere reserve natural spaces 9.04%. In Extremadura, both the number of areas under these other types of protection and the area involved is much lower than that of RN2000. Moreover, part of the surface area included in these LU was already protected as an SPA or SAC. Therefore, this work focuses on the individual analysis of the Natura 2000 network. It is also important to bear in mind that often the same landscape unit is protected by both Natura 2000 network protection categories (SPA and SAC). In other cases, a LU with SAC protection is contained in a larger LU with SPA protection or vice versa. This is why the result of fragmentation of landscape units with SPA and SAC protection can be similar in certain cases.

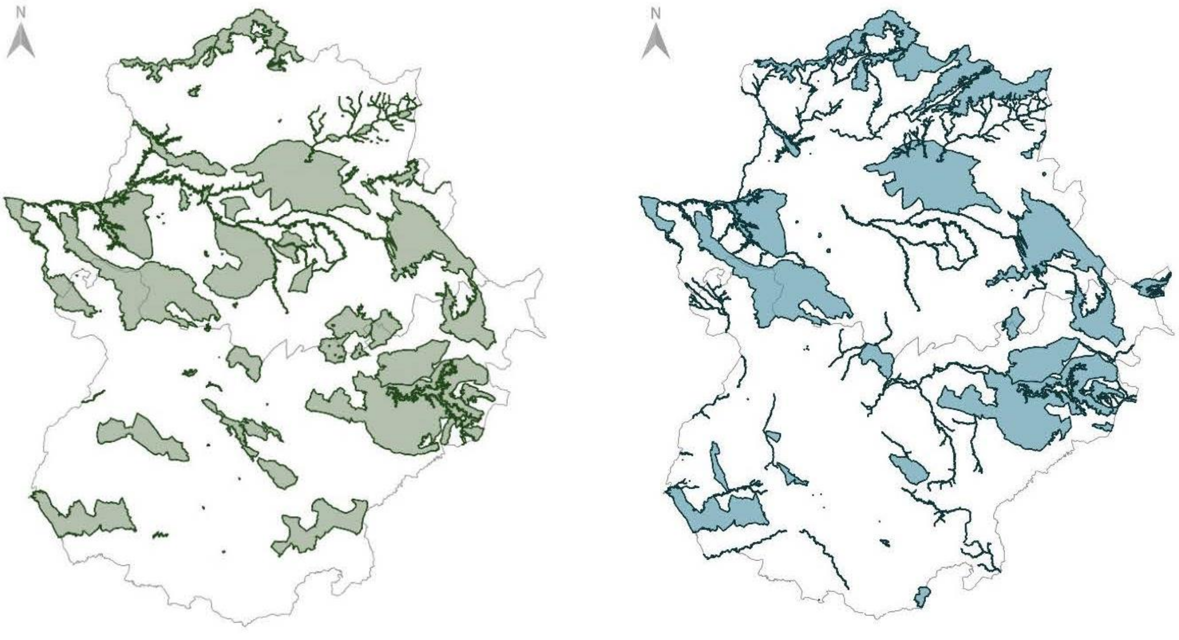
Figure 3 shows the distribution of SACs and SPAs in Extremadura according to surface area. It can be noted that 34% of the LU with SPA protection have an area larger than 10,000 ha and 61% greater than 200 ha. In the case of the SACs, 18% of the LU have an area larger than 10,000 ha and 73% have an area greater than 200 ha. The surface area is a key factor in the design of landscape units, since each animal or plant species requires a minimum amount of space in its habitat. Additionally, the larger the surface area, the greater the fragmentation that is possible due to roads and the dispersion of population settlements, as these usually seek the shortest route to connect two points.



(**a**) (**b**)

Figure 3. Statistical distribution of the surface area of Natura 2000 network protection figures in Extremadura (Spain): (**a**) SPAs and (**b**) SACs.

The spatial distribution of LU with SPA and SAC protection in Extremadura is presented in Figure 4. There are LU scattered throughout the region, although a greater concentration of these can be observed in the northern zone. The northwestern fringe is the one with the highest density of protected areas. This area is located on the border with Portugal. It is a mountainous area with some rivers and is one of the least densely populated areas, ranking 3rd out of 19 administrative units in Spain and 26th out of 746 administrative units in the European Union in 2019, [49].



(**a**) (**b**)

Figure 4. Spatial distribution of protected areas of the Natura 2000 network in Extremadura (Spain): (**a**) SPAs and (**b**) SACs [55].

2.3. Data Collection and Calculation Parameters Used

In the study of habitat fragmentation, cartographic data from different sources were used. The calculations were carried out in a Geographic Information System (GIS) environment with QGIS software [56]. The vectorial cartography used was in SHP format and the reference coordinate system is ETRS89, projected in UTM projection Huso 30N. The cartographic entities and origin of the two data types used are detailed in Table 2. It also specifies the type of vector data and the reference cartographic scale. The cartographic errors associated with the scale factor can influence the process of overlapping and intersection between layers at their edges. This can result in a loss of precision in the calculation of fragmentation indicators. This is because some of the boundaries of the environmental areas studied are roads or urban areas. The scale factor of data origin in the environmental figures is not defined in the metadata, but it is estimated to be at least 200,000, with an error associated with the scale of 40 m.

Table 2. Cartographic elements used in the study.

Element	Vector Data Type	Origin	Origin Scale Factor (m)	Error Associated with Scale (m)
Urban Area	Polygon	BCN200 IGN	200,000	40
Road Infrastructure	Line	Junta de Extremadura	200,000	40
Environmental Figures	Polygon	Junta de Extremadura	Not defined	-

The used equations include some parameters that need to be defined, such as the occlusion indices integrated in Equations (2) and (3). For the calculation of the IFI by means of Equation (2), a reference surface of $St = 1Ha$ has been established in the study. The O_i values proposed by Biondi et al. [48] and previously explained in Section 2.1 were used for both Equations (2) and (3).

In the calculation of the UFI, it is complex to use the 0_i values proposed by Romano and Tamburini [47] and transfer them directly to the fragmentation produced by the urban settlements included in an area protected by its environmental nature. The study area of the present work is mostly composed of municipalities with a population of less than 5000 inhabitants. Table 3 shows the occlusion coefficients used in this research, ordered according to the municipal population, understanding this parameter as representative of the human activity of the municipality and its size. For the calculation of the metrics in the SHP files of the linear infrastructures, the discontinuities produced by the bridges were taken into account.

Table 3. Occlusion index o_i used in the calculations with Equation (4).

Municipality Population (Inhabitants)	o_i
<5,000	0.3
5,000 – 7,500	0.4
7,500 – 10,000	0.7
10,000 – 25,000	0.8
>25,000	1

For the calculation of the IFI, given the possible cartographic errors, the following assumptions were made [27]. Road segments dividing a LU with a length of less than 5 km and patches generated with a surface area of less than 1.5 ha were not taken into account. In the calculations of the UFI, only urban areas whose surface was entirely included in the LU have been considered. Based on these parameters, the aim was to avoid possible errors produced by the design scales of the cartography used.

3. Results and Discussion

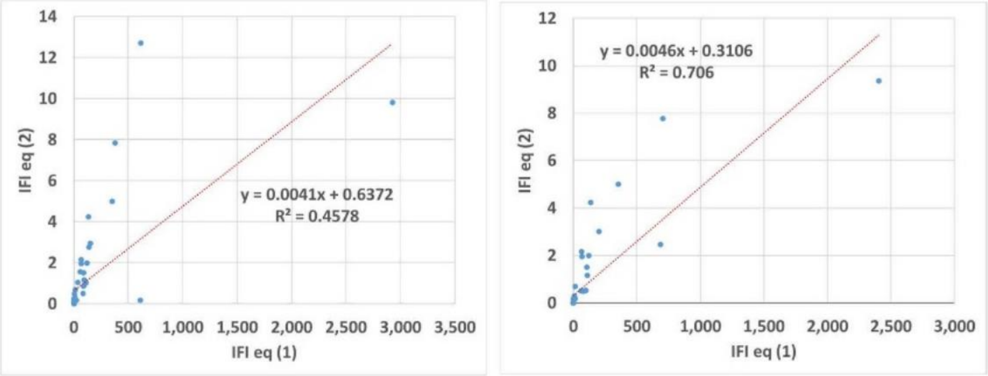
The relationship between the results found for each index IFI and UFI was first analysed by considering the different equations proposed in the literature. Secondly, a study was developed regarding relationships between the different fragmentation metrics used. Finally, a graphical analysis of fragmentation in the LU analysed in Extremadura was carried out in relation to the indices employed. This allowed for the contextualising of the LU distribution from a spatial point of view, according to their level of fragmentation.

3.1. Comparison of Metrics

3.1.1. Comparison of Equations for a Same Indicator

As pointed out in Section 2, in the case of some metrics for measuring land fragmentation, particularly the IFI and UFI, different mathematical expressions can be found in the bibliography to be evaluated. In this section, for each metric (IFI and UFI), the relationship between the values obtained with the different equations proposed was analysed. For this purpose, they were applied to two groups of natural landscape units, SPAs and SACs.

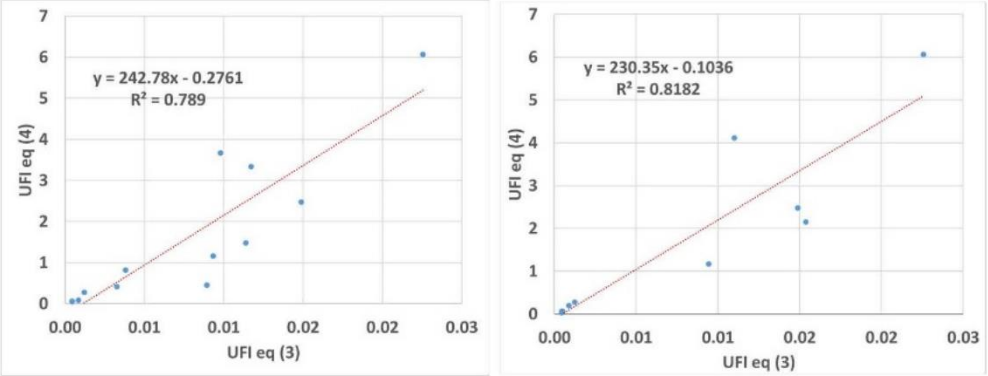
Figure 5 shows the linear relationship between the results obtained by Equations (1) and (2) proposed for the calculation of the IFI indicator when applied independently to LU with protected SPAs (Figure 5a) and SACs (Figure 5b). In both cases, a significant linear dependence was obtained at 99.9% (p value < 0.001). The explanation of the variability is 45% in the LU with SPA protection and 70% for the SACs. Given that both expressions evaluate the same cause of fragmentation of the territory, it would be expected that their results would be equivalent. However, it is observed that, in the case of SPAs, this equivalence was less than 50%, which implies the need to select one of them to obtain the fragmentation index sought. Equation (1), unlike Equation (2), takes into account in the measuring of fragmentation caused by an infrastructure not only its length and the characteristics of the road, but also aspects related to the effect of the infrastructures, through the factor $N * Pt$. Additionally, when dividing by the surface area of the area under study, the importance of the value obtained in the numerator with respect to the surface area of the landscape unit was evaluated. Consequently, the results shown in this study for the IFI were obtained using Equation (1).



(**a**) (**b**)

Figure 5. Relationship between the IFI indices calculated with Equations (1) and (2) for the protected areas of the Natura 2000 Network in Extremadura: (**a**) SPAs and (**b**) SACs.

The linear regression relationship between the obtained UFI values using Equations (3) and (4) for the LU of SPAs and SACs is shown in Figure 6. A coefficient of determination close to 0.8 and a significance of more than 99.9% was found in both cases (p value > 0.001). These results suggest that both equations evaluate the fragmentation of the territory in a similar way, so that they could be used interchangeably for the calculation of the UFI. Considering that, unlike Equation (4), Equation (3) does not take into account any aspect related to the characteristics of each urban settlement, Equation (4) was used in the analyses carried out in this paper for the UFI metric calculations.



(**a**) (**b**)

Figure 6. Relationship between the UFI indices calculated with Equations (3) and (4) for the protected areas of the Natura 2000 Network in Extremadura: (**a**) SPAs and (**b**) SACs.

3.1.2. Comparison of Different Indicators

Different studies compare or combine the indices used for the study of fragmentation of landscape units [24,27,46,47]. De Montis et al. analysed the relationship between IFI and UFI based on six landscape units. The results showed that there was no relationship; however, they determined that the number of landscape units analysed was not representative to obtain a conclusive result. The existence of a relationship between two different metrics, such as IFI and UFI, which measure the fragmentation induced in LU by different causes, would indicate that both the causes and the variables are related. Otherwise, each metric would explain different causes and effects of fragmentation.

The relationships studied in this paper between the metrics used and their significance are shown in Table 4. A significant relationship was only found between the IFI and DIVI metrics (N.S.: non-significant correlation ($p > 0.05$).

Table 5 presents the values of the linear regression parameters obtained as a result of the comparison between the IFI and DIVI for the LU of SACs and SPAs. The relationship was significant at 95% in both cases and indicates a decrease in IFI with increasing DIVI. The explanation of variability in SACs (21%) is higher than that in SPAs (15%).

Table 4. Significance (*p* value) of the relationships studied.

	IFI / UFI	IFI / DIVI	DIVI / UFI	DIVI / M_{eff}	IFI / M_{eff}	UFI / M_{eff}
SPAs	n.s.	<0.05	n.s.	n.s.	n.s.	n.s.
SACs	n.s.	<0.05	n.s.	n.s.	n.s.	n.s.

$^{n.s.}$ Non-significant correlation ($p > 0.05$).

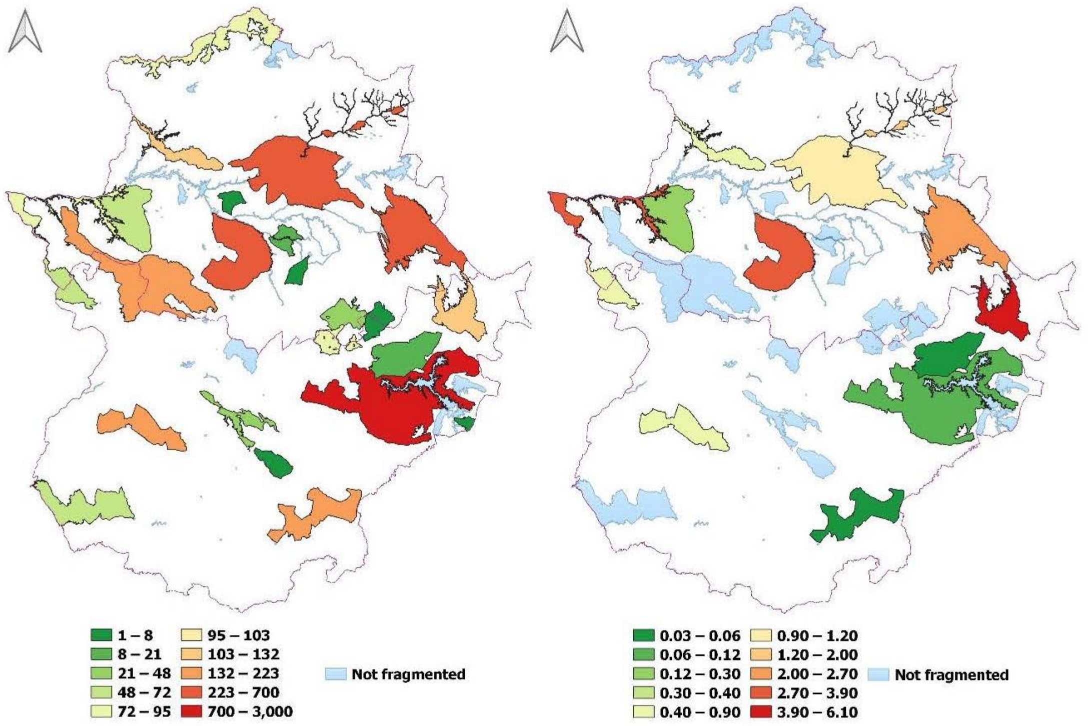
Table 5. Regression parameters of the relationship between the values of IFI and DIVI.

	R^2	m	n
SPAs	0.15	−0.0001	0.36
SACs	0.21	−0.0002	0.43

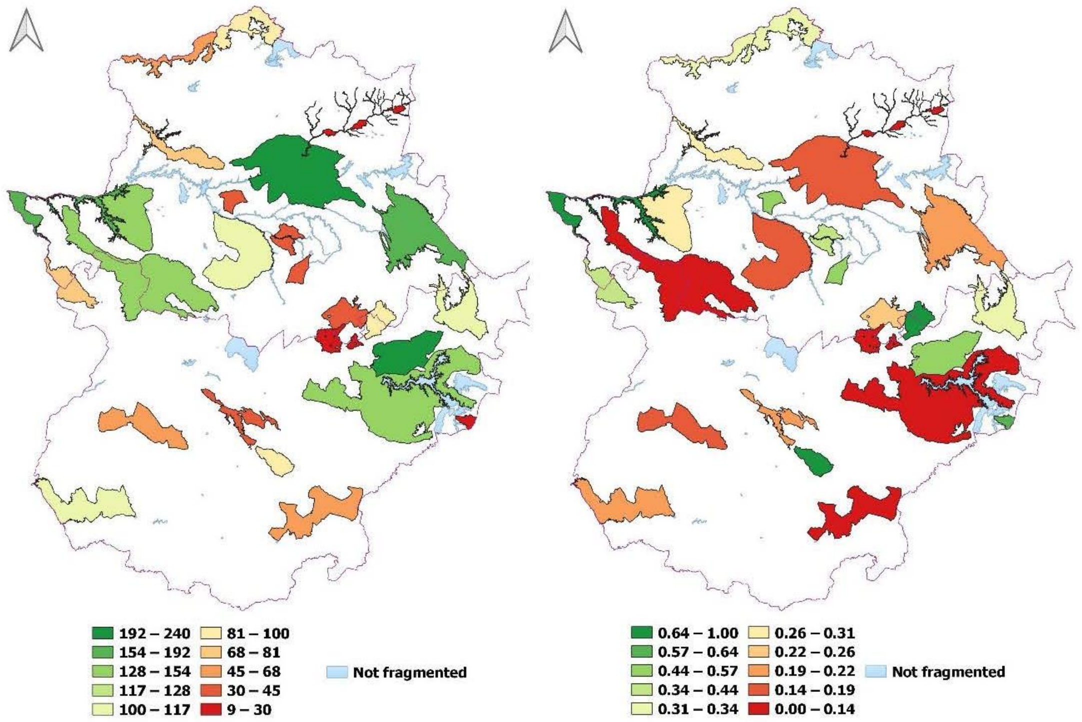
To evaluate the results that were found in this analysis, it is important to pay attention to two aspects. Firstly, it should be noted that the different indicators of landscape fragmentation proposed in the literature have been independently applied in this study for two different protected areas (SPAs and SACs) and with a large number of landscape units analysed in each of them, given that the study was framed in a scenario with a low population density and a large dispersion of urban settlements. Secondly, it can be observed that the fragmentation effect of linear infrastructures has been evaluated by means of three different indicators that have a weak or null relationship between them. Given these considerations, the results found allow us to reach two conclusions with respect to the fragmentation indicators proposed in the literature. First, it can be said that the expressions proposed for the indicators that measure the fragmentation of LU originated by linear infrastructures (IFI, M_{eff}, DIVI) evaluate different causes and consequences in the territory than the indicator proposed for the measurement of fragmentation originated by population settlements (UFI). Consequently, although the origin of transport infrastructure is in the population settlements, to evaluate the effect of human beings on the territory, it is necessary to independently consider the urban areas and the infrastructures that enable communication between them. Furthermore, the fact that only one significant relationship was found between the indicators which measure the fragmentation of the territory as a consequence of linear infrastructures seems to indicate that, as a consequence of the variables involved in these expressions or the mathematical formulation of these variables, the three expressions are basically measuring the same causes but different aspects of the consequences which linear infrastructures associated with road transport have on the territory. It should be noted that the only significant relationship found between two of these indicators (IFI and DIVI), in both types of protection, have low explanations of variability, between 15% and 21%, depending on the type of protection considered. This therefore shows that there are aspects of the effect on the territory of linear infrastructures common to both indicators, but with a weak relationship between them.

3.2. Analysis of the State of Fragmentation Based on Indicators

Considering the results shown in the previous section, it is possible to state that each of the metrics used represents the state of fragmentation of the LU under different approaches. Consequently, a comparative analysis of the fragmentation results obtained by each indicator is made in this section. To examine the importance and distribution of these fragmentation values, a graphical representation of the results obtained by means of the different indicators was firstly made separately for the different scenarios proposed in this study (71 LU of SPAs and 89 LU of SACs) and, subsequently, a detailed analysis of the results was carried out. In this context, it should be borne in mind that the IFI, UFI and M_{eff} indices show fragmentation on a scale without an upper limit, while the DIVI shows a result limited to between 0 and 1. To make it easier to compare the results between the different metrics and between the different protection figures studied, the establishment of a uniform scale of representation has been proposed. Thus, the equal count (quantile) formulation, implemented in QGIS software, was used for all the metrics. This formulation has been applied to each of the protection figures, SPAs and SACs; and, from the result, a single average scale of representation has been obtained for both. This is possible because the ranges of fragmentation values obtained in SPAs and SACs are similar. The fragmentation results obtained are graphically shown in Figure 7 for the SPAs and in Figure 8 for the SACs.

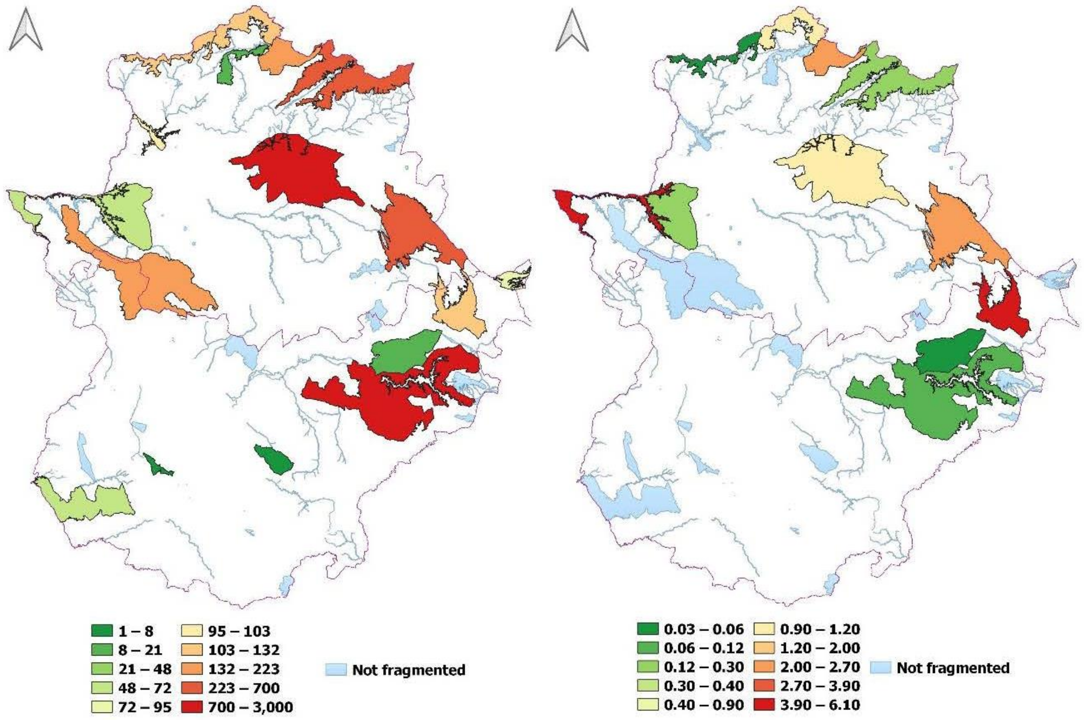


(a) (b)

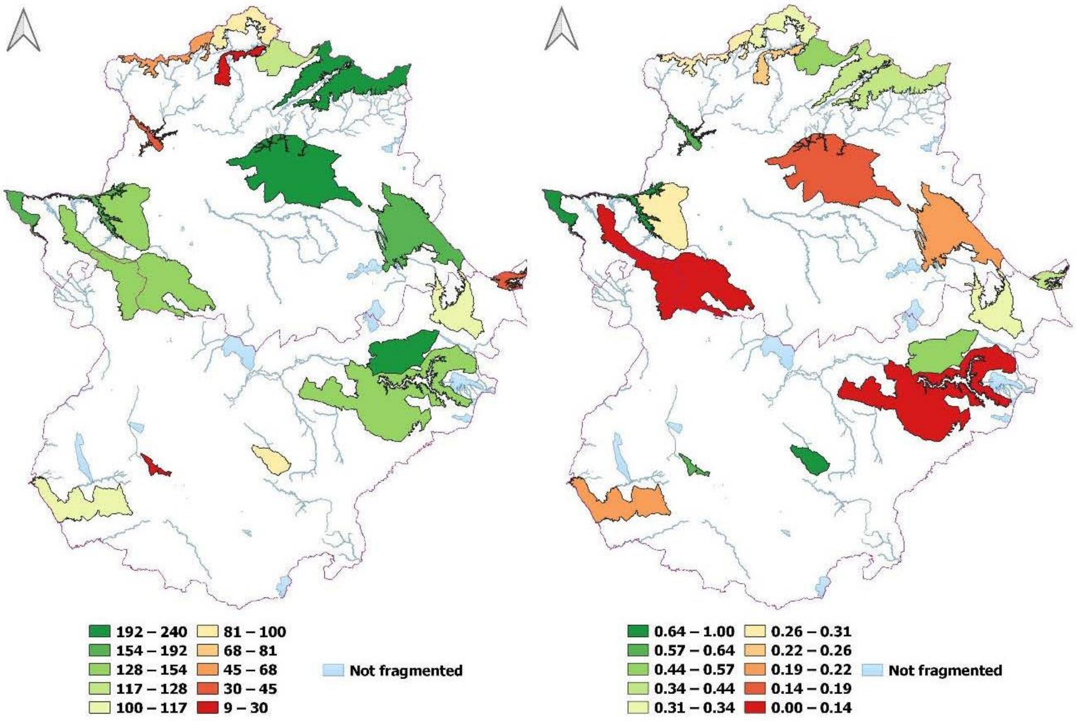


(c) (d)

Figure 7. Landscape metrics obtained in relation to the Special Bird Protection Areas (SPAs) in Extremadura (Spain): (**a**) IFI, (**b**) UFI, (**c**) M_{eff} (km^2) and (**d**) DIVI.



(a) (b)



(**c**) (**d**)

Figure 8. Landscape metrics obtained in relation to the Special Areas of Conservation (SACs) in Extremadura (Spain): (**a**) IFI, (**b**) UFI, (**c**) M_{eff} (km^2) and (**d**) DIVI.

The IFI and UFI indicators respectively analyse the fragmentation caused by road infrastructures and urban areas. In the case of the IFI (Figures 7a and 8a), it may seem that, in a first approximation, the highest values of fragmentation were obtained for the larger LU. However, a more detailed analysis shows that there are small landscape units with high values of this indicator and that similar sized areas can have very different values among them. In particular, it can be observed that, for the SPAs (Figure 7a), there are some very small LU in the northern area with high IFI values, equal to other large LU located in more central areas. In the case of the SACs (Figure 8a), other LU can also be found in the northern zone in which the IFI has very different values despite having a similar size. In fact, both figures show that areas of intermediate size can have very different values of the indicator. This is the case, for example, of the IFI values for the four SPAs located in the southern third of the European region studied (Figure 7a). Finally, it is also interesting to note that, for both protection categories, all non-fragmented LU (zero values of the IFI) have small surface areas.

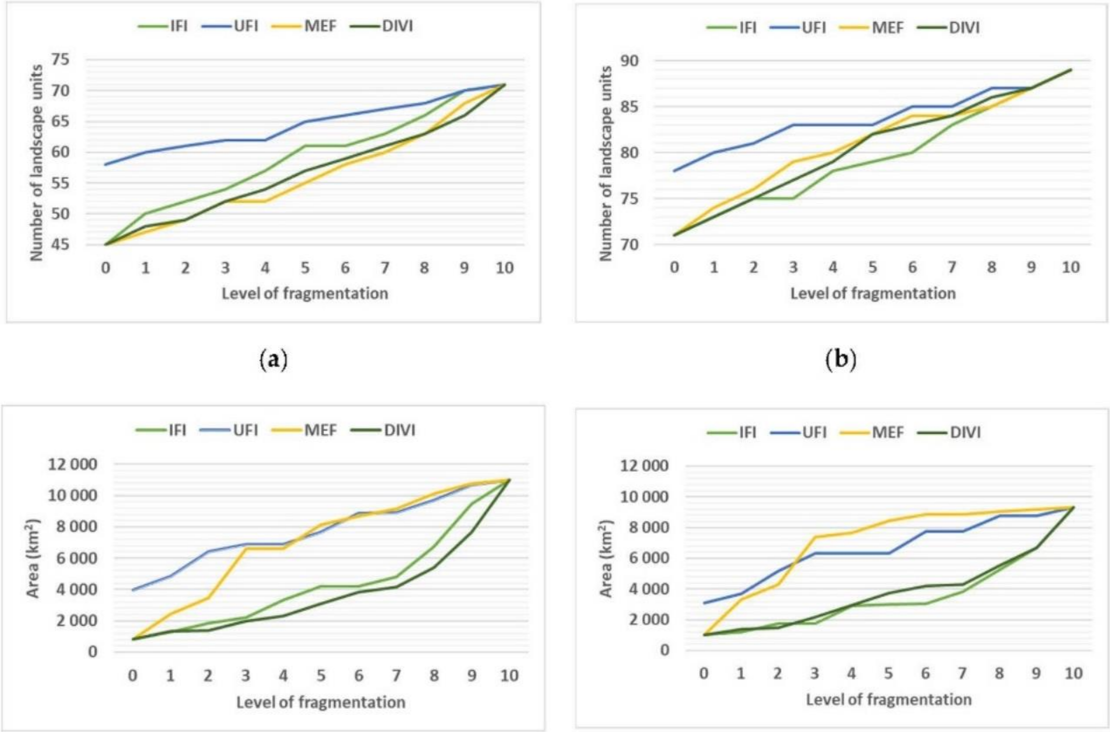
The UFI values obtained in both types of protection figures vary between 0 and 7 (Figures 7b and 8b). The representation of the results based on the UFI shows a higher proportion of non-fragmented LU, both in SACs and SPAs. Note that for the UFI, unlike the IFI, the non-fragmented LU have highly variable surfaces and no clear trend is observed relating the LU surface area to the level of fragmentation. This may be conditioned by the design of the landscape units which, in general, have been designed based on the bordering of urban perimeters. This way for designing the LU, taking into account the urban boundaries, means that the results obtained for UFI do not really reflect the influence on the LU of the neighbouring municipalities. Consequently, it is reasonable to think that the indicator is not showing the reality of fragmentation, due to the existence of municipalities close to the LU.

The M_{eff} indicator reflects the surface area (in km²) of the effective parcel of the landscape unit. The graphic representation of the values obtained from this indicator (Figures 7c and 8c) allows us to identify the adequacy degree of the LU to the environmental protection of reference, in relation to the surface necessary to preserve the protected habitat. In principle, high values of the indicator should be related to a lower level of fragmentation of the LU. If the results shown in Figures 7c and 8c are analysed, as in the case of the IFI, it is observed that the LU with a larger surface area have a higher M_{eff} value in both protection categories. This finding may be related to the fact that the larger the landscape units are, the larger the fragmented parts of the landscape may be. Consequently, this apparent correlation between the M_{eff} value and LU size should be taken with caution. It can be noted in Figures 7c and 8c that all the non-fragmented LU are of small size. In addition, some LU can be found with M_{eff} values in the zone of maximums, even though their protected areas are not among the highest values. Examples of this result can be seen in both types of protection in the LU located in the central eastern and western areas of Extremadura. For instance, it can be found that the most western LU does not have a high surface area, but its effective parcel size is in the range of maximums. It can also be detected in the central-eastern area that two LU are very close to each other and that the one with the smallest surface is the one with the largest effective parcel size. This graphical analysis of the M_{eff} values may lead to the conclusion that the M_{eff} could be more useful to identify the degree of suitability of the LU to the surface area necessary to preserve the protected habitat than as a measure of the level of fragmentation of the LU.

The results of DIVI show, as a percentage of one, the proportion of the M_{eff} over the total area of the LU. In smaller LU, this indicator makes it possible to determine whether they have been designed with criteria that are more or less suitable for the objectives. If the state of fragmentation of the region is analysed using the DIVI, both for the SPAs (Figure 7d) and the SACs (Figure 8d), a certain similarity can be observed with the results for the IFI. Therefore, to some extent, the comments made for this indicator would be valid for the DIVI, although it should be noted that many LU vary in the importance of their level of fragmentation depending on whether they are analysed with the IFI or the DIVI. This change does not always go in the same direction, although it seems that there is a tendency towards a greater measure of the fragmentation of an LU using the DIVI than using the IFI.

Based on the analysis of the results, it can be concluded that it is the combination of all indicators that allows for the identification of the shortcomings and strengths of the LU analysed and, consequently, assessment of the effectiveness of the design of the LU and the need for improvement.

To study the relative behaviour of each of the metrics in the two protection figures analysed, Figure 9 shows the fragmentation results obtained in this study by means of a cumulative representation. The results of the four indicators for the number of SPAs (Figure 9a) and SACs (Figure 9b), and for the surface area of SPAs (Figure 9c) and SACs (Figure 9d), are plotted. For this purpose, the representation ranges used in Figures 7 and 8, from the lowest (0—not fragmented) to the highest level (10) of fragmentation, have been applied. The analysis includes 71 landscape units with SPA protection (total area of 11,016 km²) and 89 landscape units with SAC protection (total area of 9332 km²).



(a) (b)

(c) (d)

Figure 9. Cumulative representation of total number of LU and total LU surface area ordered from 0 (not fragmented) and 1 to 10 from lowest to highest level of fragmentation: SPAs (**a**,**c**) and SACs (**b**,**d**).

As shown below, each protection figure and each of these two approaches (by LU units or by LU surface) allow for a different analysis of the state of fragmentation of the LU.

Given their importance, attention is focused firstly on the LU that the indicators employed report as non-fragmented. To make this analysis easier, Table 6 shows the number, surface area involved and proportions with respect to the total values of the non-fragmented LU. If the number of LU is first considered, the most remarkable feature is the high number of non-fragmented units which, at the lowest result, represent more than 63% of the LU in the region analysed. Differences can be observed between the results in SPAs and SACs, SACs being the ones with the highest number and proportion of non-fragmented surfaces. If the indicators are examined, it is the UFI indicator, which measures the effect of fragmentation caused by urban areas, that shows the highest proportion of non-fragmented LU, reaching more than 87% in the case of SACs. In some ways, these results can be interpreted as a measure of the quality of the design of the LU analysed individually; more in the case of SACs than SPAs. If this analysis is carried out in relation to the protected surface area, the results are not of equal quality and some changes occur when comparing SPAs and SACs. The non-fragmented surface area is slightly higher than 36% in the best case and only close to 8% in the worst case. Furthermore, although the values obtained using the UFI indicator are still higher, also in terms of surface area, the non-fragmented surface area measured in the SPAs using the UFI indicator is higher than that measured in the SACs. In summary, if their function of management and protection of the territory is studied, the analysis of the non-fragmented LU indicates that the design of a significant part of them has been adequate, although when considering the general design of the total protected area, the results are not so good. Regarding the design of natural areas according to the type of protection, a better design is observed for the SACs.

Table 6. Results for the number and surface area of non-fragmented landscape units.

	LU Not Fragmented	**% Relative to Total LU**	**Area Covered LU Not Fragmented (km²)**	**% Relative to Total Area**
			SPAs	
IFI, M_{eff}, DIVI	45	63.38%	845	7.67%
UFI	58	81.69%	3995	36.26%
			SACs	
IFI, M_{eff}, DIVI	71	79.78%	1027	11.00%
UFI	78	87.64%	3084	33.05%

The results are discussed below as the level of fragmentation increases. Firstly, an analysis is made of what happens in relation to the number of LU involved. It can be observed that, in both protection categories (Figures 9a and 9b), all the metrics used show a monotonically increasing trend as the level of fragmentation increases, or close to a linear behaviour. The slope of growth of the UFI is lower than that of the other three indicators, given that the number of non-fragmented units according to this indicator is higher. In addition, the growth is relatively similar among them, although with some difference in what happens in SPAs and SACs. It is observed that, in the case of SACs, the M_{eff} and DIVI indicators are close to the result of the UFI indicator in medium ranges of fragmentation, around value 5.

If the analysis of growth trends based on the surface area of the LU is now considered, basically three different behaviours can be observed, which are similar in the SPA and SAC areas. On the one hand, the UFI shows a linear trend in the relationship between fragmentation level and fragmented area. This indicator starts at higher values of non-fragmented area than the other indicators and shows an increasing monotonic variation as increasing fragmentation ranges are considered. Of the other three indicators, the M_{eff} shows a quick rise in accumulated area at low degrees of fragmentation and, subsequently, presents a monotonic growth. It is observed that, from rank 3 onwards, the UFI and M_{eff} curves accumulate similar surface areas in the case of SPAs, while in the case of SACs, the M_{eff} shows a linear trend similar to the UFI but accumulating higher surface area values. Consequently, the M_{eff} reflects the same or lower level of fragmentation than the UFI from rank 3 onwards when the surface area involved is considered. If the growth of the surface area is analysed for the IFI and DIVI indicators, a similar behaviour is observed, with a slow and monotonous growth of the accumulated surface area that is maintained until high fragmentation ranges are reached (rank 7). From this range onwards, there is a fast increase in surface area.

4. Conclusions

The present study assessed the fragmentation degree of the landscape units of the Natura 2000 network in the European region of Extremadura. A separate analysis has been carried out for two typologies of protection of the Natura 2000 network, Special Bird Protection Areas (SPAs), and Special Areas of Conservation (SACs). For this purpose, the IFI, UFI, M_{eff} and DIVI fragmentation indices were used.

As different expressions are proposed in the scientific literature to calculate IFI and UFI fragmentation indices, a comparative analysis was carried out for the expressions of each index. For IFI, non-uniform results were found and, in the case of SPAs, the equivalence between expressions was only 45%. For this reason, the equation that considers a greater variety of factors associated with habitat fragmentation due to linear infrastructure was selected for IFI calculation in this research. For the UFI, the two proposed equations in the literature for assessing the fragmentation of the territory are related, but the equation that takes into account a specific detail of urban configuration was considered the most suitable for calculating the UFI in this study.

As a consequence of the comparison made between the results obtained for the indicators IFI, UFI, M_{eff} and DIVI, it can be concluded that those indicators which measure the fragmentation of the territory as a consequence of linear infrastructures (IFI, M_{eff} and DIVI), although they consider the same causes, are evaluating different consequences that road transport has on the territory. It can also be concluded that the expressions proposed for the indicators which measure the fragmentation of LU originated by road infrastructures (IFI, M_{eff} and DIVI) evaluate different causes and consequences in the territory than the indicator proposed for the measurement of fragmentation originated by urban settlements (UFI). As a general conclusion for the analysis of all indicators used, it can be stated that each of the indicators identifies shortcomings and strengths of LU of a different nature, so that a combination of these is necessary to assess the effectiveness of the design of the landscape units and needs for improvement.

Considering each of the two protection categories of the Natura 2000 network (SPAs and SACs) and each of the two approaches proposed to study the landscape units (by number of LU or by LU surface), different analyses of the state of fragmentation can be carried out. If the number of LU is first taken into account, a high number of non-fragmented LU was found (>63%) and the UFI was the indicator with the highest proportion of non-fragmented LU (>87% for SACs). However, when the analysis is performed under the LU surface criterion, the non-fragmented surface of the studied area ranges between approximately 8% and 36%, depending on the case. In summary, the design of a significant number of LU seems to be adequate, although when considering the general design of the total protected area, the results were not so good. Regarding the design of natural areas according to the type of protection, a better design is observed for the SACs. When analysing what happens in terms of the number of LU units and LU surface as the level of fragmentation increases, the results obtained for the Natura 2000 protected areas in Extremadura show a general increasing trend for the indicators IFI, UFI, M_{eff} and DIVI, although with some differences in the slope depending on the type of protected areas (SPAs and SACs) and the criterion applied (by LU units or by LU surface).

The differences found based on the criteria for studying the state of fragmentation, the metrics used and the environmental protection figure for LU make the definition of the state of fragmentation of an environmental area a complex process, which must be approached from multiple points of view in order to obtain a rigorous result. Consequently, the combination of metrics and approaches carried out in this study can be a comprehensive method for the analysis of territorial fragmentation due to road infrastructures. This analysis could provide the administration and other potential stakeholders with a tool to guide decision-making on territory and road infrastructure management and new approaches to the organisation of the Natura 2000 network.

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CAPÍTULO 4. AFECCIÓN ACÚSTICA DEL RUIDO DE TRÁFICO A LAS CARRETERAS.

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Relationship between temperature and road traffic noise under actual conditions of continuous vehicle flow

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ABSTRACT

This paper focuses on studying the influence of temperature on the sound pressure level of tire-road noise emission using continuous environmental noise measurements. *In situ* noise measurements were performed next to a primary road under free flowing traffic where tire-road noise emission dominates, while simultaneously monitoring the air and pavement temperature. The broadband results showed a variation in noise level with temperature, with a ratio of -0.058 ± 0.007 dBA/°C for the pavement temperature and -0.161 ± 0.020 dBA/°C for the air temperature. A 1/3 octave band analysis revealed a decrease in sound level with increasing temperature in the fundamental bands of road traffic noise emission, and similar behaviour and values to that observed in the broadband analysis. The physical media in which temperature is measured appears to be important. Several implications may arise from this work in regard to reference standards for noise evaluation, calculation and measurement.

1. Introduction

This paper presents an experimental study of the relationships between temperature and environmental noise level generated by road traffic on a primary road. The tire-road noise emission is analysed for a mixed traffic under road operating conditions and for a dense asphalt. *In situ* noise measurements were performed in both broadband and frequency bands, while simultaneously monitoring the temperature of both the air and the pavement. This approach allows an approximation to this question by considering a mixed traffic flow including both light and heavy vehicles simultaneously, unlike research under controlled conditions.

The noise generated by road traffic is a source of environmental pollution that has adverse effects on the general population (Cai et al., 2020; Lan et al., 2020; Ma et al., 2021; Thacher et al., 2020) and on wildlife (Connelly et al., 2020; Finch et al., 2020; Iglesias-Merchán et al., 2016). Road traffic noise is also closely related to air pollution and its impacts on people's health (Andersson et al., 2020; Franklin and Fruin, 2017; Puyana-Romero et al., 2020). In this context, the European Environmental Noise Directive (European Directive, 2002) considers this type of infrastructure the main source of noise pollution, and requires the use of strategic noise maps (Barrigón Morillas et al., 2021; Khan et al., 2021; Lan and Cai, 2021; Wosniacki and Zannin, 2021) to provide a basis for assessing the environmental impact and for the design of measures for noise mitigation (Fredianelli et al., 2019; Montes-González et al., 2019; Paschalidou et al., 2019).

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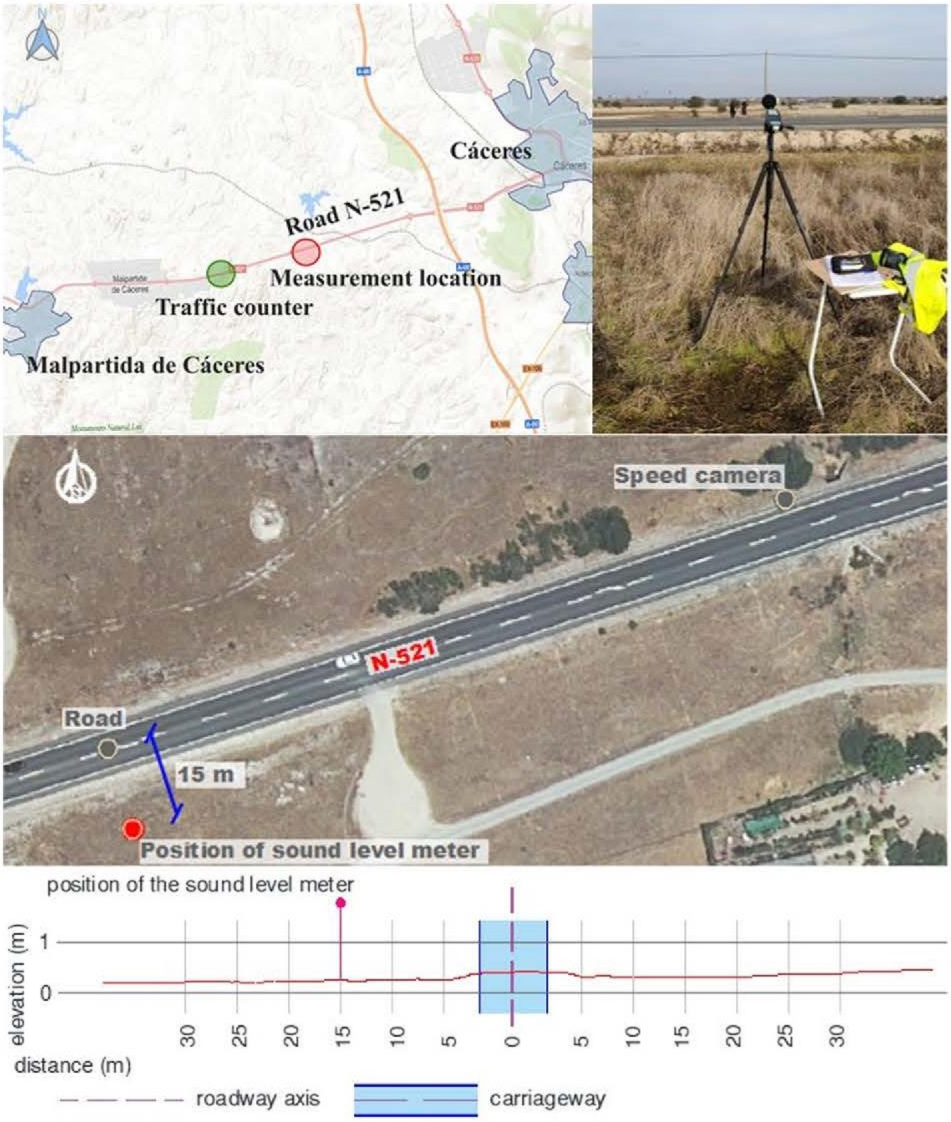

Fig. 1. Location, plan view and cross-sectional profile of the measurement site.

Factors influencing the noise levels from roads can be classified into three groups: infrastructure characteristics, traffic characteristics and environmental conditions. Infrastructure characteristics are variables that can be controlled during the process of designing, modifying or maintaining roads, and these include the type of pavement, the state of conservation, and the geometric design. Vázquez et al. (Vázquez et al., 2018a) found that the dynamic stiffness and the macrotexture of cold in-place recycled pavement are more important conditioning factors in the generation of tyre/road noise at medium frequencies than for other conventional hot bituminous mixtures. They also evaluated the medium-term evolution of the surface features of urban pavements, such as the rolling noise and mean profile depth (MPD), and concluded that the MPD may be related to pavement ageing and hence to the evolution of the tyre/pavement noise (Vázquez et al., 2018b). Del Pizzo et al. (Del Pizzo et al., 2020) identified a positively correlated zone for low frequency emission and a negatively correlated region at higher frequencies, by analysing 10 road surfaces in terms of their CPX noise and texture levels. Licitra et al. carried out a study that demonstrated the importance of the type of tyre on the sound pressure level generated on low-noise road surfaces (Licitra et al., 2017).

Compared to factors associated with the infrastructure itself, the characteristics of the traffic (such as the flow, speed, vehicle typology, intrinsic characteristics or tyres) are more difficult to control. Rey Gozalo et al. (Rey Gozalo et al., 2019) observed a clear influence from the number and percentage of heavy vehicles on the uncertainty in noise maps, and found it hard to estimate the traffic speed in connection with noise mapping. The speed and vehicle typology are widely studied parameters that also condition the sound pressure level generated in tyre-road noise (Cho and Mun, 2008; Institute for Vehicle Technology, 2005).

Meteorological factors also affect both the propagation and the generation of sound energy. Standards for the assessment of environmental noise generally consider propagation in a broad way, but often do not clearly address issues related to noise generation (ISO 1996-1, 2016; ISO 1996-2, 2017; ISO 9613-1, 1993; ISO 9613-2, 1996). In this regard, ISO 11819-1, ISO 11819-2 and ISO/PAS

Fig. 2. Details of the road surface.

11819-4 (ISO/PAS 11819-4, 2013; ISO 11819-1, 1997; ISO 11819-2, 2017) cover the assessment of tyre/road noise and do not cover environmental noise emissions from road traffic. ISO 11819-1 standard (ISO 11819-1, 1997) indicates that sound levels should be corrected to a reference air temperature of 20 °C, but does not go so far as to propose a specific way to make this correction. ISO 11819-2 (ISO 11819-2, 2017) also establishes a reference air temperature of 20 °C and proposes a temperature correction of the sound level based on a coefficient given in ISO/TS 13471-1:2017 (ISO/TS 13471-1, 2017) that is only valid for two specific tires and not for a general circulation fleet. The value of this coefficient varies between −0.04 and −0.11 dBA/°C according to the type of surface and the speed of the vehicles. Values of between −0.05 and −0.10 were also proposed as standard for three different types of road surfaces, but these were independent of speed. The influence of air and pavement temperature on the generation of sound pressure levels has been explored by several researchers (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann et al., 2015; Bühlmann and Ziegler, 2011; Jabben, 2013; Kneib et al., 2016; Liao et al., 2015; Sandberg, 2015; Yuan et al., 2019) who based their studies on reference standards for the acoustic characterisation of pavements under controlled traffic conditions (ISO/PAS 11819-4, 2013; ISO 11819-2, 2017). Bühlmann and Van Blokland carried out a review where a great variety of results were shown for the relationship between tyre-road noise and temperature (Bühlmann and Van Blokland, 2014). To the best of the present authors' knowledge, there have been no studies in which the effect of temperature on the sound level of a road transport infrastructure has been measured under actual conditions of continuous vehicle flow. Jabben (Jabben, 2013) conducted a study in which the maximum sound pressure level, (LAmax), recorded for individual vehicles in a free flowing traffic was analysed. Prior analyses carried out under these standards have examined the effect of temperature on the sound pressure level generated as a function of variables such as pavement porosity and the types of tyres, vehicles and pavement. In these studies, the relationship between sound pressure level and air or pavement temperature has generally been determined by means of linear relationships, and the values found for the coefficients ranged between −0.03 and −0.11 dBA/°C. In some of these works, an analysis of this effect in the 1/3 octave bands has also been carried out, and the results have shown different behaviours depending on the frequency (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011). As a general rule, a higher linear relationship between temperature and sound level has been observed in frequency ranges of 31.5–630 Hz and 1.6–5 kHz, where the coefficients are mostly negative. However, the ISO/TS 13471-1:2017 standard (ISO/TS 13471-1, 2017) points out that the data collected in this way are not sufficiently consistent to allow for a frequency-dependent temperature correction, and therefore suggests that the same correction should be applied for all frequencies. In this regard, the recently proposed Common Noise Assessment Methods in Europe (CNOSSOS-EU) (European Directive, 2015) for strategic noise mapping uses a correction to the sound power emitted by road traffic to reflect the decrease with increasing air temperature. Based on a broadband analysis, CNOSSOS-EU proposes the application of a generic coefficient of −0.08 dB/°C for light vehicles (category 1) and −0.04 dB/°C for heavy vehicles (categories 2 and 3) for all asphalts, while for octave band analyses, these same correction coefficients are applied to all octave bands from 63 Hz to 8 kHz, without distinguishing between low, medium and high frequencies.

2. Methodology

2.1. *Study area*

On-site measurements were carried out on the N-521 road in Extremadura, Spain, in the section between the towns of Cáceres and Malpartida de Cáceres (Fig. 1). As discussed below, the point of measurement was chosen based on the characteristics of the road geometry, good pavement conditions, the proximity of an official speed camera and the average daily traffic (ADT). It was located 5 km from Malpartida de Cáceres, on a straight section of 3.4 km (plan view) with a horizontal cross section in the measurement area. There were no obstacles between the microphone and the road that could cause acoustic shielding effects (Montes González et al., 2020b; Van Blokland et al., 2014) and no reflective surfaces behind it that could produce sound reflections (Memoli et al., 2008; Montes González et al., 2020a) (Fig. 1).

The traffic flow in this section is monitored by the Ministry of Transport (Spanish National Government) using a traffic counter.

Based on the data recorded over the last ten years, the ADT on this stretch of road is 7658 vehicles, of which 7256 are light vehicles (95.1%) and 378 are heavy vehicles (4.9%). It can therefore be estimated that it has an annual flow that is close to the limit of three million vehicle passages established by the European Environmental Noise Directive (European Directive, 2002) at which it would be considered a major road. An estimated value of 600 vehicles per hour during the day could be expected based on the ADT.

This is a seven-year-old road surface that can be assumed to be a dense asphalt. Its wearing course is composed of 8 cm of bituminous concrete AC22S in the lower layer, and 3 cm of discontinuous bituminous mix BBTM 11B in the upper part (Ministry of Transport of Spain, 2015). The discontinuous bituminous mix BBTM 11B has a void content greater than 12% and a surface macrotexture greater than 1.5 mm (see Fig. 2). The parameters of percentage of voids and MPD were measured when the pavement was laid. These data were provided by the Ministry of Transport, Mobility and Urban Agenda. This surface corresponds to the NL01 class, in accordance with CNOSSOS-EU (European Directive, 2015). The area adjacent to the road was mainly grass, and could be considered acoustically absorbent (Fig. 1).

2.2. *Measurement procedure*

In order to analyse the effect of temperature on the noise generated under actual conditions of continuous vehicle flow, the study needed to be designed in such a way that the variables or conditions that could influence the measured sound level were taken into account throughout the experimental procedure.

The obvious first step was to consider the variability in the characteristics of the passing vehicles, their typology and the numbers of vehicles driving past the microphone within a given unit of time.

There is a wide range of types of vehicle, and the maintenance conditions for both the vehicles and the tyres also vary. In order to obtain a suitable average of their effects on the noise level, the measurement time was selected to ensure that at least 100 vehicles passed in front of the measurement point. Based on the official ADT, a measurement time of 10 min was selected.

The speed limit on the stretch of road under study was 100 km/h, and an official speed camera was located close to the measuring point (Fig. 1). Measurements at this point showed that the average speed of the vehicles was slightly lower than the speed limit, and that the majority of the vehicles were travelling at within ±5 km/h of the average speed. Maximum variations of about 1 dBA were estimated for light and heavy vehicles for variations in speed of ±5 km/h (Institute for Vehicle Technology, 2005). The variability in sound level associated with vehicle speed was averaged over a total number of passing vehicles that was equal to or greater than 100, in the same way as for the vehicle characteristics (ISO 11819-1, 1997).

The noise level generated by traffic will also depend on the category of the vehicle. The category and flow of vehicles were visually monitored for each lane of traffic, and four categories of vehicle were identified based on CNOSSOS-EU (European Directive, 2015), as follows: Category 1: light motor vehicles; Category 2: medium heavy vehicles; Category 3: heavy vehicles; Category 4: powered two-wheelers. The last of these had two subcategories: Category 4A: mopeds; Category 4A: motorcycles.

As indicated above, only about 5% of the traffic did not fall into the category of light vehicles, meaning that its effect on the variability in the different measurements of the equivalent continuous sound level may not be significant. However, its possible effect was evaluated in this study by using an equivalence factor between the different vehicle typologies and light vehicles, following approaches previously used in the scientific literature (Sandberg, 2003; U.S. Department of Transportation, 2015).

A microphone with a windshield was located 15 m from the centre of the road (Sandberg, 2003) and at a height of 1.5 m from the ground, in order to make *in situ* measurements, as shown in Fig. 1 (ISO 1996-2, 2017; Montes González et al., 2020c; RSG, 2018). The equivalent sound pressure level was recorded in the broadband ($L_{eq,A}$) and 1/3 octave bands (L_{Xeq}) using a class 1 sound level meter/analyser. Thirty-six 10-minute measurements were carried out in two campaigns on different days. The calibration of the sound level meter was verified before and after each series of measurements.

The relative humidity, air temperature, wind speed and pavement temperature were recorded at the beginning and end of each measurement. The relative humidity and air temperature were measured at a height of 1.5 m above the ground (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011; ISO 11819-2, 2017) using a thermo-hygrometer sensor with an accuracy of ±1%; this was placed in the shade to ensure that direct sunlight did not affect the measurement. The pavement temperature was measured using a thermal camera with a sensitivity of <0.045 °C (reading temperature range −20 to +120 °C) at a single position on the side of the road and across the nearest lane from the location of the sound level meter. The camera was placed at a height of 1.5 m with an angle of 45° with respect to the horizontal. Before and after each measurement, a thermal image of the traffic lane was taken on the tread. The roadway temperatures were extracted from the thermal images, and the average was calculated (Bueno et al., 2011).

2.3. *Data processing*

As explained previously, the deviations in sound level that are associated with differences in speed and vehicle characteristics could be counterbalanced through the use of an average sound pressure level recorded over a 10-minute period, during which the number of vehicles registered was at least 100 (ISO 11819-1, 1997; ISO 1996-2, 2017). A similar average value of the sound power generated per vehicle unit is expected for all of the measurements taken. However, the number of vehicles that pass by is not expected to be the same in each 10-minute period. This means that the equivalent continuous sound level recorded in each measurement period will be influenced by the total number of vehicles that have passed in front of the microphone during that period. To take this fact into account, it is necessary to normalise the results against a reference flow. An average value of 780 vehicles/hour was recorded on site, and the normalised sound pressure level L_N was obtained from Eq. (1):

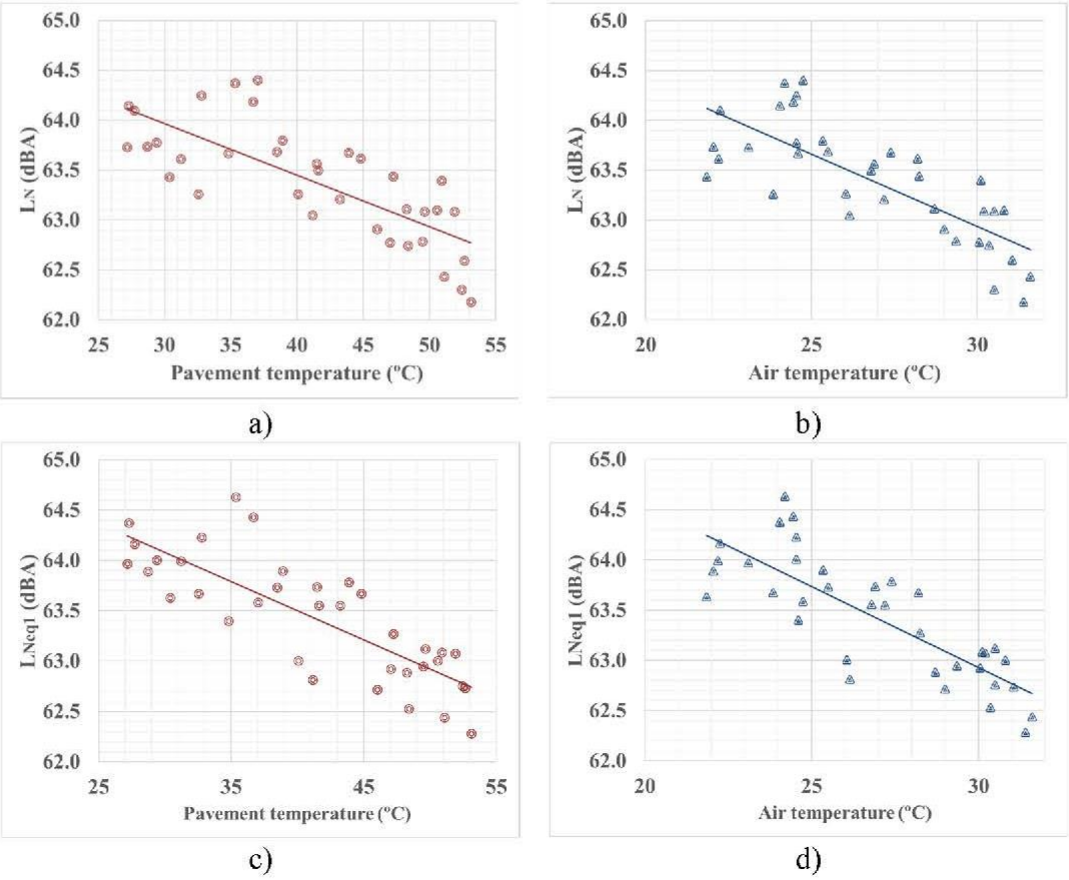

Fig. 3. Scatter diagrams and linear regression between the normalised sound levels (L_N and L_{Neq1}) and temperature.

$$L_N = L_0 - 10^{*}log_{10}\left(\frac{V_m}{780}\right) + 10^{*}log_{10}\left(\frac{t_m}{60}\right) \tag{1}$$

whereL_0 is the recorded sound pressure level; V_m is the total number of vehicles recorded in 10 min; and t_m is the measurement time in minutes.

Although the proportion of non-light vehicles recorded is less than 10% overall, the sound power emitted by these categories of vehicles can be considered different from that of category 1 vehicles (Cho and Mun, 2008; Institute for Vehicle Technology, 2005). To examine the possible influence of these vehicles on the results, a second normalisation was performed by considering the equivalence between the noise level emitted by category 1 vehicles and the rest of the vehicle categories, as shown in Eq. (2). The coefficients for vehicle categories 2, 3 and 4 in Eq. (2) were obtained by (Sandberg, 2003) based on a speed of 95 km/h for categories 1 and 4, and 90 km/h for categories 2 and 3.

$$V_{eq1} = V_{m1} + V_{m2}{}^{*}3.83 + V_{m3}{}^{*}6.31 + V_{m4} \tag{2}$$

where V_{eq1} is the equivalent total number of vehicles in category 1, and V_{mi} is the number of vehicles in category i (European Directive, 2015).

Again, the total equivalent number of vehicles in category 1 is not likely to be the same in each measurement, and another normalisation was therefore applied in order to analyse the relationship between the measured noise level and the temperature. The equivalent vehicle value V_{eq1} obtained from Eq. (2) was normalised based on the average total equivalent category 1 vehicle flow in the measurements (a total equivalent of 930 category 1 vehicles per hour). In a similar way as above, the category 1 equivalent normalised sound pressure level L_{Neq1} was derived from Eq. (3):

$$L_{Neq1} = L_0 - 10^{*}log_{10}\left(\frac{V_{eq1}}{930}\right) + 10^{*}log_{10}\left(\frac{t_m}{60}\right) \tag{3}$$

where L_0 is the recorded sound pressure level; V_{eq1} is the total number of equivalent vehicles in category 1; and t_m is the measurement time in minutes.

Table 1

Linear regression parameters between the sound pressure level and the air and pavement temperatures.

Independent variable	Dependent variable	β_i (dBA/°C)	*Standard error* β_i (dBA/°C)	Constant (dBA)	R^2	*Sig.*
T_P	L_N	−0.051	0.008	65.5	0.58	< 0.001
T_P	L_{Neq1}	−0.058	0.007	65.8	0.66	< 0.001
T_A	L_N	−0.146	0.020	67.3	0.60	< 0.001
T_A	L_{Neq1}	−0.161	0.020	67.8	0.66	< 0.001

Table 2

Regression and determination coefficients between the sound level and temperature reported in scientific literature.

Publication	$\beta_a \frac{dBA}{Â°C}$	$\beta_p dBA/Â°C$	R^2 *Air / pavement*	Method	Temperature range *Air / pavement*
Present researchL_N	−0.146	−0.051	0.58 / 0.60	Actual conditions of continuous vehicle flow	22–32 / 27–53
Present researchL_{Neq1}	−0.161	−0.058	0.66 / 0.66		
(Anfosso-LédéE and Pichaud, 2007)	−0.100	−0.060	0.92 / 0.86	CPB	0–30 / 0–50
(Bueno et al., 2011)	–	−0.060	- / n/d	CPX	- / 15–50
(Bühlmann and Ziegler, 2011)	−0.100 / −0.110[1]	–	0.8 / -	CPX	10–30 / -
(Liao et al., 2015)	−0.090	–	0.36 / -	OBSI	5–30 / -
(Yuan et al., 2019)	–	−0.086 / −0.081	- / n/d	SPB	- / 5–22

[1] Depending on the type of tyre used.

3. Results and discussion

3.1. Environmental and traffic variables

During the sound level measurements, the environmental variables of wind speed, relative humidity and air and pavement temperatures (T_A)and (T_P) were recorded. The wind speed was zero in most of the readings, and lower than 2 m/s even in the worst case. The relative humidity varied between 27% and 63%. The air temperature ranged from 22 °C to 32 °C, while the pavement temperature varied from 27 °C to 53 °C. A significant linear relationship between the air and pavement temperatures was found ($p < 0.001$), with a coefficient of determination R^2 of 0.93. This result is similar to values reported by other authors (Anfosso-LédéE and Pichaud, 2007; Rochat, 2009).

The average traffic flow recorded on site was 130 vehicles per measurement (780 vehicles/h). The distribution by vehicle category was as follows: category 1: 93.46%; category 2: 3.27%; category 3: 1.70%; and category 4: 1.57%.

3.2. Broadband analysis

As indicated in the methodology section, a study of the relationship between the sound level and temperature required a normalisation of the sound levels in order to take into account the differences in traffic flow during the measurement period. This normalisation was carried out in two phases. Firstly, given the low traffic flows measured for vehicle categories other than type 1, an average value for the sound power per vehicle using Eq. (1) was assumed. Then, despite the low proportions of vehicle categories 2, 3 and 4, the effect that their presence had on the relationship between noise level and temperature was considered of interest. Eqs. (2) and (3) were used to carry out this normalisation. The results for the relationships between the sound level and the pavement and air temperatures are shown in Fig. 3 and Table 1.

Fig. 3(a) shows the linear relationship between the equivalent normalised sound pressure level L_N and the pavement temperature T_P, which can explain 58% of the variability of the measured sound level with a probability of more than 99.9% (see Table 1). The coefficient of variation of the sound level with the temperature of the pavement ($\beta_p dBA/Â°C$) has a value of -0.051 ± 0.008 dBA/°C, representing a decrease in sound level with an increase in pavement temperature. The dependence of the sound level on the air temperature was then analysed, and Fig. 3(b) shows a linear relationship that explains 60% of the variability (p-value < 0.001). In this case, the coefficient of variation obtained for the air temperature ($\beta_A dBA/Â°C$) was $-0.146 \pm 0.020 dBA/Â°C$, which, in terms of its absolute value, is clearly higher than that obtained for the pavement temperature even considering its standard error. This increase in β is evidently related to the smaller range of variation in the air temperature with respect to the pavement temperature. Despite the close relationship between the two temperatures ($R^2 = 0.93$), these findings reflect the importance of the physical media in which the temperature is measured, in terms of determining the value of the coefficient of dependence of the sound level on this environmental variable.

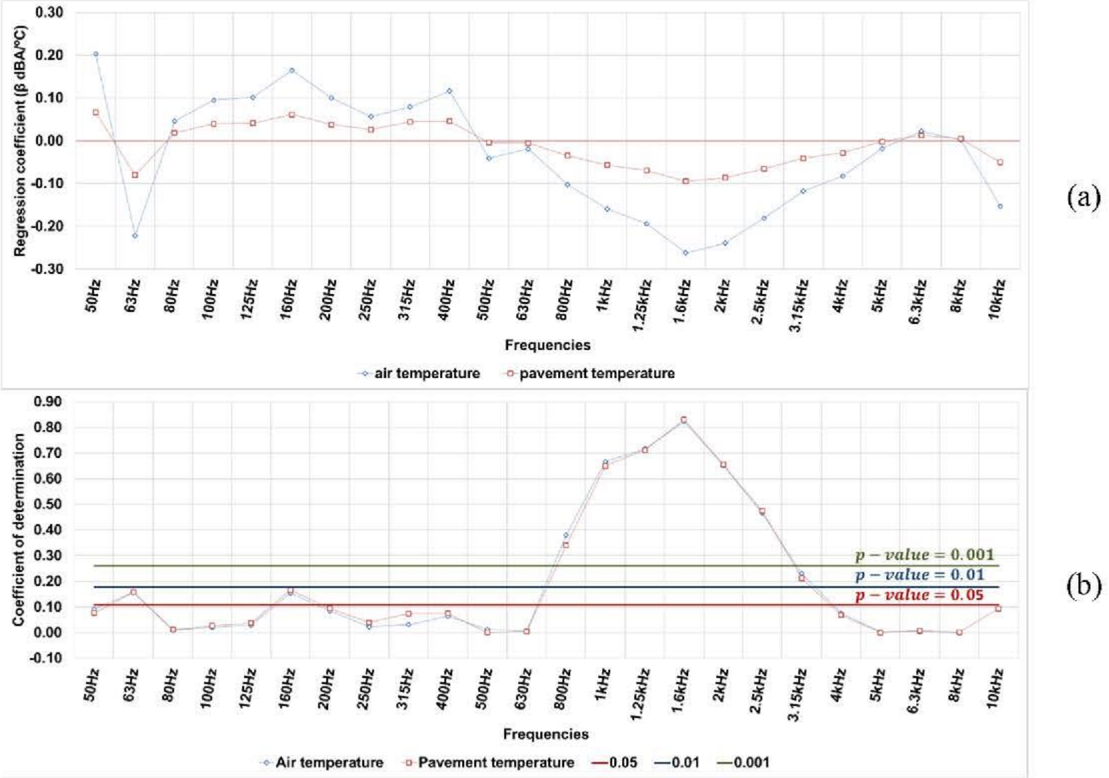

Fig. 4. Regression and determination coefficients for the linear relationship between the normalised sound pressure level (L_N) and the air and pavement temperatures in the 1/3 octave bands.

The effect of considering vehicles other than category 1 on the relationship between sound level and temperature was then analysed using Eqs. (2) and (3). The results for the relationship of the sound pressure level normalised to equivalent category 1 vehicles (L_{Neq1}) and the pavement temperature are shown in Fig. 3(c). The linear relationship between these variables explains 66% of the variability in the measured sound level as a function of pavement temperature, with a significance lower than 0.001; this represents an increase in the explanation of the variability of sound levels when all categories of vehicles were considered. The $\beta_P$coefficient is equal to $-0.058 \pm 0.007dBA/\hat{A}^{\circ}C$ in Fig. 3(c). A value of $\beta_A = -0.161 \pm 0.020dBA/\hat{A}^{\circ}C$ was found for the relationship between L_{Neq1} and T_A (Fig. 3(d)). This linear relationship can explain 66% of the variability in the sound level with air temperature, with a p-value < 0.001. Hence, when air temperature is considered, this second normalisation (Eqs. (2) and (3)) also provides an improvement in the explanation of the variability in the measured sound levels. Although the values of the slopes of the lines shown in Fig. 3 (c) and Fig. 3 (d) are slightly higher than those in Fig. 3 (a) and Fig. 3 (b) in absolute values, this increase is not significant considering the standard error of the slopes.

In summary, taking into consideration all of the vehicle categories improves the determination of noise emission levels as a function of either the pavement or the air temperature, even though the proportion of vehicles other than category 1 is low.

These results were then compared with those obtained in previous studies of pavements of the same type (Table 2) (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011; Liao et al., 2015; Yuan et al., 2019). In this respect, it must be taken into consideration that this is a seven-year-old dense mixture. Some studies used the air temperature to obtain the coefficient of variation in the sound pressure level with temperature (Bühlmann and Ziegler, 2011; Liao et al., 2015), while others derived the coefficient from the pavement temperature (Bueno et al., 2011; Yuan et al., 2019). Anfosso-Lédée and Pichaud (Anfosso-LédéE and Pichaud, 2007) determined the coefficients for both temperatures, in this case using the CPB method. They obtained a coefficient of variation in the sound level for a dense pavement of $-0.100dBA/^{\circ}\mathrm{C}$ using the air temperature, and $-0.060dBA/^{\circ}\mathrm{C}$ from the pavement temperature.

Of the researchers who examined only the air temperature, (Bühlmann and Ziegler, 2011) reported a coefficient of variation of -0.100or $-0.110dBA/^{\circ}\mathrm{C}$, depending on the type of tyre, using the CPX method, while Liao et al. (Liao et al., 2015) found a value of $-0.090dBA/^{\circ}\mathrm{C}$ using the OBSI method.

Of the researchers who investigated only the pavement temperature, Bueno et al. (Bueno et al., 2011) obtained a coefficient of variation of $-0.060dBA/^{\circ}\mathrm{C}$ from the CPX method. Yuan et al. (Yuan et al., 2019) conducted a study using the CPB method in which they considered three driving speeds (40, 60 and 80 km/h) and two different vehicles, and calculated coefficients of variation of $-0.086dBA/^{\circ}\mathrm{C}$, $-0.083dBA/^{\circ}\mathrm{C}$ and $-0.081dBA/^{\circ}\mathrm{C}$ for these three speeds, respectively.

For the air temperature, the results presented in this paper were above the range of variation reported in previous studies, which

Table 3
Linear regression parameters (slope, standard error of slope, R^2 and p-value of R^2) between the sound pressure level L_N in the 1/3 octave bands and the air and pavement temperatures.

Fr.	**50 Hz**	**63 Hz**	**80 Hz**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**
Low frequencies	Pavement temperature							
m	0.07	−0.08	0.02	0.04	0.04	0.06	0.04	0.03
$\widehat{\sigma}_m$	0.04	0.03	0.03	0.04	0.04	0.02	0.02	0.02
R²	0.08	0.16	0.01	0.03	0.04	0.17	0.09	0.04
Sig.	n.s.	< 0.05	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.
	Air temperature							
m	0.20	−0.22	0.05	0.09	0.10	0.16	0.10	0.06
$\widehat{\sigma}_m$	0.11	0.09	0.08	0.11	0.10	0.07	0.06	0.06
R²	0.09	0.16	0.01	0.02	0.03	0.15	0.08	0.02
Sig.	n.s.	< 0.05	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.

Fr.	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1 kHz**	**1.25 kHz**	**1.6 kHz**	**2 kHz**
Mid-frequencies	Pavement temperature								
m	0.04	0.05	0.00	−0.01	−0.04	−0.06	−0.07	−0.09	−0.09
$\widehat{\sigma}_m$	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01
R²	0.07	0.08	0.00	0.00	0.34	0.65	0.71	0.83	0.66
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Air temperature								
m	0.08	0.12	−0.04	−0.02	−0.10	−0.16	−0.19	−0.26	−0.24
$\widehat{\sigma}_m$	0.08	0.08	0.06	0.04	0.02	0.02	0.02	0.02	0.03
R²	0.03	0.06	0.01	0.01	0.38	0.67	0.72	0.82	0.65
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Fr.	**2.5 kHz**	**3.15 kHz**	**4 kHz**	**5 kHz**	**6.3 kHz**	**8 kHz**	**10 kHz**
High frequencies	Pavement temperature						
m	−0.07	−0.04	−0.03	0.00	0.01	0.01	−0.05
$\widehat{\sigma}_m$	0.01	0.01	0.02	0.02	0.02	0.02	0.03
R²	0.47	0.21	0.07	0.00	0.01	0.00	0.09
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	n.s.
	Air temperature						
m	−0.18	−0.12	−0.08	−0.02	0.02	0.00	−0.15
$\widehat{\sigma}_m$	0.03	0.04	0.05	0.05	0.07	0.07	0.07
R²	0.47	0.23	0.08	0.00	0.00	0.00	0.11
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	< 0.05

were conducted using standardised test methods and under controlled conditions in terms of the vehicles and tyre-road surface. The results obtained in this study for the dependence of sound level on pavement temperature were within the range of variation of previous investigations (Table 2).

When the coefficients of variation for the sound level with temperature (β_i) reported in the scientific literature are compared, higher values were obtained when the air temperature was considered rather than the pavement temperature; this broadly corresponds to the results of the present study, although the values of the coefficients found in this paper were greater than those in the literature.

3.3. *Spectral analysis*

To provide a detailed analysis of the dependence of sound level on temperature, the broadband analysis was complemented by a study in the 1/3 octave bands in the range 50 Hz to 10 kHz. In the same way as for the broadband analysis, the sound pressure levels were normalised to a reference flow L_N (Eq. (1)) and to the equivalent flow of category 1 vehicles L_{Neq1}(Eqs. (2) and (3)). These calculations were carried out for both the air and pavement temperatures.

Fig. 4 and Table 3 show the results for the relationship between L_N and the air and pavement temperatures. In the case of Fig. 4 (b), considering that the number of data used in the regression is the same for the different frequencies analysed, the value of the coefficient of determination for which it was significant with a probability of 95%, 99% and 99.9% was obtained. Thus, the horizontal lines in Fig. 4 (b) indicate the p-values of 0.05, 0.01 and 0.001. At low frequencies, significant relationships were observed in the 63 Hz and 160 Hz third octave bands for both temperatures (p-value < 0.05), although with a low explanation of variability of between 15% and 17%. The slope at 63 Hz implies a decrease in sound level with increasing temperature (-0.08 ± 0.03 dB/°C for T_P and -0.22 ± 0.09 dB/°C for T_A), with similar behaviour to the broadband results. In contrast, the slope found in the 160 Hz band is positive (0.06 ± 0.02 dB/°C for T_P and 0.16 ± 0.07 dB/°C for T_A), indicating an increase in sound level with increasing temperature.

The next bands in which significant relationships were found corresponded to the range 800 Hz to 3.15 kHz. The relationship between sound pressure level and temperature in this band range is negative, and has a greater absolute value for air temperature than for pavement temperature, for the same reasons as identified in the broadband analysis. It was also observed that except for the 3.15 kHz band, the frequency bands showed correlations with a significance lower than 0.001, low standard errors of slopes, and high

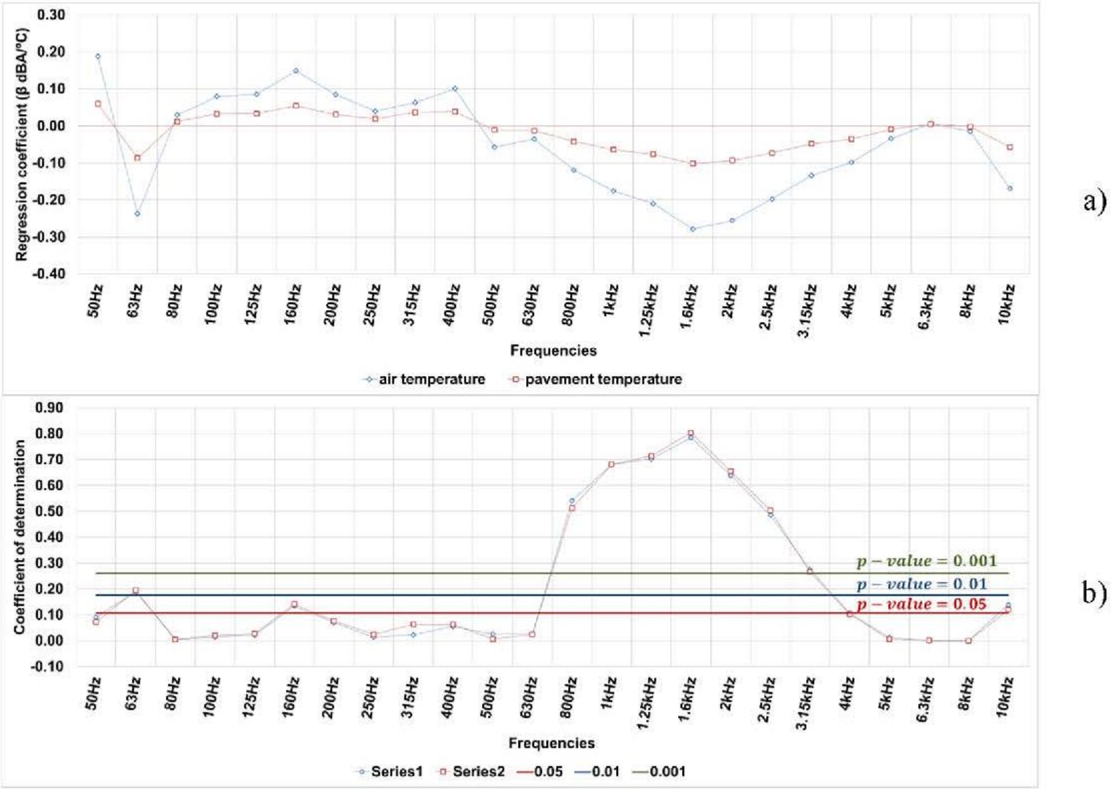

Fig. 5. Regression and determination coefficients for the linear relationship between the category 1 equivalent normalised sound pressure level (L_{Nequ1}) and the air and pavement temperatures in the 1/3 octave bands.

explanations of the variability in the sound level with temperature. The results in the third octave bands between 1 and 2 kHz are particularly remarkable, where the R^2 values varied between 0.65 and 0.83, indicating sound level variation coefficients ranging from -0.06 ± 0.01 to -0.09 ± 0.01 dB/°C for T_p and -0.16 ± 0.02 to -0.26 ± 0.02 dB/°C for T_A (Table 3). For the rest of the high frequency bands, significant relationships (p-value < 0.05) were only found in the 10 kHz band for T_p. The explanation of the variability in the sound level was also low (11%) and a standard error of about 50% of the slope value.

Fig. 5 and Table 4 present the results for the relationships between the L_{Neq1} values and the air and pavement temperatures. The horizontal lines in Fig. 5 (b) indicate the different levels of significance of the coefficient of determination, analogous to Fig. 4 (b). In general, these show similarities to those obtained for L_N (Fig. 4 and Table 3). At low frequencies, significant relationships with temperature were again found only for sound levels measured in the 63 and 160 Hz bands. The slope was negative in the first case ($\beta_P = -0.09 \pm 0.03dB/\hat{A}°C$; $\beta_A = -0.24 \pm 0.08dB/\hat{A}°C$), and positive in the second ($\beta_P = 0.06 \pm 0.02dB/\hat{A}°C$; $\beta_A = 0.15 \pm 0.06dB/\hat{A}°C$). However, while the significance in the 160 Hz band was still 95%, it improved to 99% in the 63 Hz band. The next frequency range in which a significant relationship with temperature was found appeared between 800 Hz and 3.15 kHz, with similar p-values to those found for the previous normalisation. However, the results for the 800 Hz band were noteworthy, as the variable L_{Neq1} could explain more than 50% of the variation in the sound level with temperature, while the figure for the variable L_N was lower than 40%. For the rest of the high-frequency bands, significant relationships (p-value < 0.05) were again only found in the 10 kHz band, although in this case they applied to both temperatures.

When the results are analysed and both normalisations are compared, it can be seen that the 1/3 octave bands of 63 and 800 Hz are the main ones at which the combined effects of the different vehicle categories are the strongest; that is, it can be said that the emission power in these bands behaves in a similar way to that indicated for the equivalences considered for category 1 (Sandberg, 2003).

From a comparison between the findings of this research and those in the literature, it can be observed that several authors (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011) have reported results with a similar trend for the range 800 to 3.15 kHz. The result for the 10 kHz band could not be compared with previous publications, as no analysis had been performed above 5 kHz (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011). Regarding the results in the low-frequency bands, it is worth highlighting one paper (Bühlmann and Ziegler, 2011) in which positive values were obtained for the coefficients of variation in the sound pressure level with temperature, although this result was discarded in the subsequent analysis. A. del Pizzo et al. (Del Pizzo et al., 2020), in their study of the dependence of pavement texture on road traffic noise using the CPX method, found a positive linear relationship between sound pressure level and megatexture at low frequencies and negative at high frequencies associated with macrotexture. This paper also indicated the relation between this behaviour and the different generation mechanisms that dominate the two regions: tyre vibrations for low frequency and aerodynamic mechanisms for high frequency. It

Table 4
Linear regression parameters (slope, standard error of slope, R^2 and p-value of R^2) between the category 1 equivalent normalised sound pressure level (L_{Nequ1}) in the 1/3 octave bands and the air and pavement temperatures.

Fr.	**50 Hz**	**63 Hz**	**80 Hz**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**
Low frequencies	Pavement temperature							
m	0.06	−0.09	0.01	0.03	0.03	0.06	0.03	0.02
$\hat{\sigma}_m$	0.04	0.03	0.03	0.04	0.04	0.02	0.02	0.02
$\mathbf{R^2}$	0.07	0.19	0.01	0.02	0.03	0.14	0.08	0.02
Sig.	n.s.	< 0.01	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.
	Air temperature							
m	0.19	−0.24	0.03	0.08	0.09	0.15	0.08	0.04
$\hat{\sigma}_m$	0.10	0.08	0.08	0.11	0.10	0.06	0.05	0.06
$\mathbf{R^2}$	0.09	0.19	0.00	0.01	0.02	0.13	0.07	0.01
Sig.	n.s.	< 0.01	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.

Fr.	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1 kHz**	**1.25 kHz**	**1.6 kHz**	**2 kHz**
Mid-frequencies	Pavement temperature								
m	0.04	0.04	−0.01	−0.01	−0.04	−0.06	−0.08	−0.10	−0.09
$\hat{\sigma}_m$	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01
$\mathbf{R^2}$	0.06	0.06	0.01	0.02	0.51	0.68	0.71	0.80	0.65
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Air temperature								
m	0.06	0.10	−0.06	−0.04	−0.12	−0.18	−0.21	−0.28	−0.26
$\hat{\sigma}_m$	0.07	0.07	0.06	0.04	0.02	0.02	0.02	0.02	0.03
$\mathbf{R^2}$	0.02	0.05	0.03	0.03	0.54	0.68	0.70	0.78	0.64
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Fr.	**2.5 kHz**	**3.15 kHz**	**4 kHz**	**5 kHz**	**6.3 kHz**	**8 kHz**	**10 kHz**
High frequencies	Pavement temperature						
m	−0.07	−0.05	−0.03	−0.01	0.01	0.00	−0.06
$\hat{\sigma}_m$	0.01	0.01	0.02	0.02	0.02	0.02	0.03
$\mathbf{R^2}$	0.50	0.27	0.10	0.01	0.00	0.00	0.12
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	< 0.05
	Air temperature						
m	−0.20	−0.13	−0.10	−0.03	0.01	−0.01	−0.17
$\hat{\sigma}_m$	0.03	0.04	0.05	0.05	0.07	0.07	0.07
$\mathbf{R^2}$	0.49	0.27	0.11	0.01	0.00	0.00	0.14
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	< 0.05

seems therefore that the low frequency emission range may require specific studies.

4. Conclusions

An experimental study of the relationship between the air and pavement temperatures and the road traffic noise levels on a primary road under actual conditions of continuous vehicle flow is presented in this manuscript. Several variables or circumstances that can influence the measured sound level were taken into account.

Some key findings can be drawn from the broadband results. When the temperature was taken at the road surface, the coefficients of variation in the sound level with temperature were similar to those published in the scientific literature under controlled conditions, following the reference standards. However, when the air temperature was considered, the coefficients of variation in sound level with temperature were higher than previously published results recorded under controlled conditions in dense pavements. Despite the high proportion of light vehicles in the mixed traffic on the road (over 92%), normalising to a flow of vehicles equivalent to category 1 was found to improve the explanation of the variability of sound level with temperature, regardless of the physical media in which the variable was measured.

Several conclusions could also be derived from the spectral analysis in the 1/3 octave bands. In the fundamental noise emission bands of road traffic, the trends in the dependence of sound level on temperature coincided with the published outcomes, resulting in a decrease of the sound level with increasing temperature. However, the values of the coefficients of variation depended on the physical media in which the temperature was measured. Thus, when the temperature of the pavement was measured, the slopes were similar to those published in the scientific literature, while when the air temperature was taken into account, the slopes were greater than those previously reported. Another finding of note is the positive value of the coefficient of variation in the sound level with temperature in the 160 Hz band, which implies an increase in the sound level with increasing environmental temperature; this effect has not previously been reported.

From a comparison of the spectral results with and without normalisation to category 1 equivalent vehicles, no appreciable effects relating to the type of normalisation were found in most frequency bands, in contrast to the results of the broadband analysis. However, noticeable improvements were observed in the 1/3 octave bands of 63 and 800 Hz and 3.15 kHz for the normalisation of vehicles equivalent to category 1.

The results found in this study for traffic noise, obtained on a road in actual conditions of use with dense asphalt and mixed and continuous flow of vehicles, are not necessarily transferable to other types of pavements or flows. The possibility of applying this type of study to the temperature corrections for strategic noise maps indicates the need for further research with methodologies that allow to measure the effect of temperature on the equivalent continuous sound level in other situations: other types of asphalt, other types of flows, other proportions of light and heavy vehicles, etc. In the other hand, the possible importance of the physical media in which the environmental temperature is measured in terms of assessing the correction factors for the effects of temperature on the sound level should be highlighted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CAPÍTULO 5. CONCLUSIONES GENERALES

Las conclusiones obtenidas en esta tesis doctoral están detalladas en los capítulos 3 y 4 del presente documento, como parte de las publicaciones científicas realizadas. El documento abarca un estudio de fragmentación del paisaje a causa de las carreteras, en el que se comparan 4 métricas de fragmentación del paisaje; y la evaluación de la relación ruido-temperatura para el ruido de rodadura en carreteras como consecuencia del tráfico.

Para la evaluación de la fragmentación de hábitats, se han empleado 4 métricas de fragmentación, aplicadándolas sobre las unidades del paisaje de la Red Natura 2000 que existen en Extremadura. El estudio realizado muestra resultados no equivalentes entre cada una de las métricas empleadas; en consecuencia, pone de manifiesto que la elección de la métrica condiciona las conclusiones obtenidas.

Las métricas de fragmentación de hábitats son una herramienta de ordenación y planeamiento del territorio que permiten realizar un seguimiento del grado de fragmentación de las unidades del paisaje, permitiendo evaluar el coste de fragmentación que supone la modificación del elemento disruptivo, en este caso las carreteras. Para la fragmentación a causa de las carreteras, se considera necesario combinar las métricas IFI, Meff y DIVI con el fin de disponer de un punto de vista global de las consecuencias de fragmentación que actúan en un determinado caso. La ausencia de valores de referencia en las diferentes métricas definidas para evaluar el nivel de fragmentación del paisaje a causa de las infraestructuras lineales, implica que solo es posible saber si unas unidades del paisaje se encuentran más o menos fragmentadas que otras. Por ello, los resultados obtenidos mediante las métricas empleadas en esta tesis no permiten indicar si el valor de fragmentación representa un nivel de fragmentación adecuado o si sugieren la necesidad de una revisión de la configuración de unidad del paisaje e infraestructuras existentes.

El ruido generado por el tráfico de las carreteras, dadas las velocidades de uso de las infraestructuras viarias, se origina fundamentalmente por la rodadura; esto es, en el contacto neumático-carretera. Este contaminante puede ser entendido como una barrera física no visible, consecuencia de la explotación de las infraestructuras viales. Su generación está condicionada por múltiples variables. Estas variables pueden ser agrupadas en las pertenecientes a las características técnicas de la vía (trazado y pavimento), a las características de los vehículos de los usuarios (tipología y estado de los neumáticos) y a las condiciones meteorológicas. En esta tesis se ha evaluado la relación del nivel de presión sonora continuo equivalente con la temperatura ambiental, tanto del pavimento como del aire, en una carretera en régimen de funcionamiento con un tráfico mixto. Los resultados obtenidos en este trabajo han permitido que, por primera vez en la literatura científica, se hayan medido, en condiciones de uso de una infraestructura del transporte por carretera y promediando sobre un conjunto de vehículos en tráfico mixto, los efectos de la temperatura sobre el ruido de rodadura. Los resultados encontrados en este trabajo muestran que existe una relación significativa entre la temperatura y el nivel de presión sonoro generado por el tráfico rodado. Los valores encontrados para caracterizar esa dependencia se encuentran en los rangos de los reflejados en estudios realizados por otros autores, con similares objetivos, pero bajo el uso de normas de referencia internacionales para la medida bajo condiciones controladas. La relación ha sido estudiada empleando el método de regresión lineal y los resultados implican una disminución del nivel de presión sonoro con el incremento de la temperatura. Las normativas de medición de nivel sonoro relacionado con el ruido neumático-carretera e instrucciones de cálculo de mapas de ruido no contemplan con exactitud la incidencia de la temperatura en el nivel de presión sonora. El experimento realizado plantea un punto de partida para el estudio de otros tipos de pavimentos y otras configuraciones del tráfico con el objetivo de establecer con precisiones crecientes la corrección a aplicar al nivel de presión sonora medido en relación con la temperatura del aire o pavimento. Esto permitiría poder realizar comparaciones, de forma adecuada, entre resultados de medidas realizadas en diferentes circunstancias o entre medidas y valores predichos mediante el uso de modelos de cálculo. Todo ello, finalmente, redundaría en una mejor evaluación del efecto final que las infraestructuras del transporte van a tener sobre los entornos naturales en los que se asientan. Además, el estudio realizado podría tener también su continuidad en la evaluación, en condiciones normales de uso, de la dependencia del nivel sonoro con la temperatura en ámbitos urbanos.

CAPÍTULO 6. LÍNEAS FUTURAS

En el campo de fragmentación de hábitats, se ha evaluado el encaje de las métricas actualmente existentes en el contexto de la Red Natura 2000 de una región de gran extensión, baja densidad de población y gran proporción de superficie protegida ambientalmente. Los resultados muestran que estas métricas no son equivalentes entre sí, de modo que se requieren varias métricas para obtener un punto de vista amplio del valor de fragmentación de una unidad del paisaje; en consecuencia, se plantea, como línea de futuro, la investigación sobre nuevas métricas que, agrupando los aspectos más relevantes que recogen las actualmente propuestas en la literatura, tanto en lo referentes a las causas de la fragmentación como en lo relativo a sus consecuencias, permitan obtener valores de fragmentación de hábitats que representen una visión integral del estado en el que se encuentran las unidades del paisaje bajo estudio.

La evaluación y control de las emisiones de ruido en las infraestructuras viarias aún plantea retos en la normalización de diferentes variables que, aun estando reflejadas en normas y recomendaciones de medida y generación de modelos, no están suficientemente justificadas, como es el caso de la variación del nivel de presión sonora generado con la temperatura. En este trabajo se han evaluado la variación del nivel de presión sonoro con la temperatura para una carretera de calzada única, doble sentido de circulación y tráfico mixto. La metodología empleada queda validada por los resultados obtenidos. Esta metodología se puede aplicar para ampliar el conocimiento de la relación entre temperatura y nivel de presión sonora en situaciones con variaciones concretas, como flujos de tráfico con un mayor porcentaje de vehículos pesados, o pavimentos tipo con un volumen de huecos diferente. Los estudios planteados pueden ser empleados para mejorar la definición de normas de medida y guías de cálculos en las que se basan los softwares de modelado para la elaboración de mapas de ruido.

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HITOS CONSEGUIDOS

Los hitos originados a partir del planteamiento inicial de esta tesis doctoral se han clasificado según tres ítem: Artículos en revistas científicas, a fecha de depósito de tesis han sido publicados dos documentos científicos en revistas indexadas en JCR; Comunicaciones en congresos internacionales, han sido presentadas tres comunicaciones; Y proyectos obtenidos en convocatorias competitivas, la idea de tesis ha permitido obtener dos proyectos de I+D+i que han impulsado el desarrollo de los trabajos presentados.

1. Artículos en revistas científicas

- ***Impact of Roads on Environmental Protected Areas: Analysis and Comparison of Metrics for Assessing Habitat Fragmentation.***
  - **Autores:** Sánchez-Fernández, Manuel; Barrigón Morillas, Juan Miguel; Montes González, David & de Sanjosé Blasco, José Juan
  - **DOI:** https://doi.org/10.3390/land11101843
  - **Revista y editorial:** Land, MDPI
  - **Impacto:** JCR – Q2 área ENVIRONMENTAL STUDIES (56/128)
  - **Aportación del autor de la tesis doctoral**: Es primer autor de la publicación. Ha intervenido en el diseño de la investigación, obtención de los datos y cálculo, análisis de resultados, obtención de conclusiones y elaboración del borrador y del documento final.
- ***Relationship between temperature and road traffic noise under actual conditions of continuous vehicle flow***
  - **DOI:** https://doi.org/10.1016/j.trd.2021.103056
  - **Autores:** Sánchez-Fernández, Manuel; Barrigón Morillas, Juan. Miguel; Montes González, David & Rey Gozalo, Guillermo
  - **Revista y editorial:** Transportation Research Part D: Transport and Environment – Elservier.

  - **Impacto:** JCR – Q1 área TRANSPORTATION SCIENCE & TECHNOLOGY (9/40)
  - **Aportación del autor de la tesis doctoral**: Es primer autor de la publicación. Ha intervenido en el diseño de la investigación, obtención de los datos y cálculo, análisis de resultados, obtención de conclusiones y elaboración del borrador y del documento final.

2. **Congresos internacionales**

- ***Evaluación de la fragmentación de hábitats de la Red Natura 2000 en Extremadura***
  - **Autores:** Sánchez-Fernández, Manuel; Barrigón Morillas, Juan Miguel; Montes González, David & de Sanjosé Blasco, José Juan
  - **Congreso:** IV INTERNATIONAL CONGRESS ON SUSTAINABLE DEVELOPMENT
  - **Impacto:** Internacional
  - Azores (Portugal)
  - **Aportación del autor de la tesis doctoral:** Es primer autor del trabajo. Ha intervenido en el diseño de la investigación, obtención de los datos y cálculo, análisis de resultados, obtención de conclusiones y elaboración del borrador y del documento final
- ***A methodological proposal to measure rolling noise under real road use conditions***
  - **Autores:** Atanasio Moraga, Pedro; Sánchez-Fernández, Manuel; Rey Gozalo, Guillermo; Montes González, David; Vílchez-Gómez, Rosendo; Bachiller León, Alicia y Barrigón Morillas, Juan Miguel
  - **Congreso:** INTERNOISE 2022
  - **Impacto:** Internacional
  - Glasgow (Reino Unidi)
  - **Aportación del autor de la tesis doctoral:** Es segundo autor del trabajo. Ha intervenido en el diseño de la investigación, obtención

    de los datos y cálculo, análisis de resultados, obtención de conclusiones y elaboración del borrador del documento.

- ***Relationship between tyre-road noise and temperatura under noncontrolled traffic flow conditions***
    - **Autores:** Sánchez-Fernández, Manuel; Montes González, David; Barrigón Morillas, Juan Miguel; Atanasio Moraga, Pedro; Rey Gozalo, Guillermo; Vílchez-Gómez, Rosendo y Bachiller León, Alicia
    - **Congreso:** EUROREGIO 2022
    - **Impacto:** Internacional
    - Aalborg (Denmark)
    - **Aportación del autor de la tesis doctoral:** Es segundo autor del trabajo. Ha intervenido en el diseño de la investigación, obtención de los datos y cálculo, análisis de resultados, obtención de conclusiones y elaboración del borrador del documento.

3. Proyectos obtenidos en convocatorias competitivas.

A partir de la idea de tesis doctoral, planteada en el año 2016 por el autor de la tesis doctoral y los directores de la misma, han sido conseguidos dos proyectos competitivos que han contribuido y financiado el desarrollo de ésta.

- RESOLUCIÓN de 6 de septiembre de 2019, de la Secretaría General, por la que se aprueba la convocatoria de las subvenciones para el fomento de la contratación de personal de apoyo a la investigación en la Comunidad Autónoma de Extremadura, correspondiente al ejercicio 2019-2020. (DOE 191, jueves 3 de octubre de 2019).
    - **Título del proyecto:** Evaluación del efecto del diseño de las infraestructuras viarias en el control del ruido.
    - **Investigador principal:** Juan Miguel Barrigón Morillas
    - **Tipología de convocatoria:** Convocatoria para la contratación de un técnico como personal investigador que desarrolle el proyecto.

  - **Método de adjudicación:** Convocatoria competitiva convocada por la Universidad de Extremadura. Se valora el proyecto solicitado y el currículum del investigador principal.
  - **Fuente de Financiación:** Servicio Extremeño público de empleo (SEXPE). Consejería de Educación y Empleo de la Junta de Extremadura. Fondo Social Europeo, Unión Europea (FSE)
  - **Aportación del autor de la tesis doctoral:** Personal investigador contratado para el desarrollo del proyecto.
- ORDEN de 7 de mayo de 2019 por la que se aprueba la convocatoria de las ayudas destinadas a financiar la realización de proyectos de investigación industrial y desarrollo experimental a las empresas de la Comunidad Autónoma de Extremadura (DOE 96, martes 21 de mayo de 2019).
  - **Título del proyecto:** IDA2-19-0022-3. Afección ambiental de las carreteras en Extremadura. fragmentación de hábitat por condicionantes propios de la carretera (geométricos) y derivados de la fase de explotación de la infraestructura (tráfico y ruido) (DOE Nº34, viernes 19 de febrero de 2021)
  - **Empresa Líder:** PATH Ingeniería Civil S.L.
  - **Método de adjudicación:** Convocatoria competitiva convocada por la Junta de Extremadura. Se valora la calidad del proyecto presentado.
  - **Fuente de Financiación:** Consejería de Economía, Ciencia y Agenda Digita. Fondo Europeo de Desarrollo Regional, Unión Europea (FEDER)
  - **Aportación del autor de la tesis doctoral:** Personal investigador, coordinador del proyecto en la empresa líder.

APÉNDICE A. LISTADO DE FIGURAS

APÉNDICE B. LISTADO DE TABLAS