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The 17th International Road Federation (IRF) World Meeting constitutes an extraordinary opportunity to bring together the international community that works every day for a better and greater development of road network, as well as sharing the latest advances in planning, project engineering, construction, maintenance and operation of roads. In addition, it becomes an opportunity to set up a joint definition of the challenges of the future.

Roads are, in essence, the infrastructure that allows the highest flow of both passengers and goods, while plays a main role to society as for its contribution to economic growth and social cohesion. Furthermore, roads are transport infrastructures that have historically experienced a significant development in several countries, becoming a key factor in their progress. However, we must continue putting our efforts into them, in order to continuously improve their performance, providing a better level of service for final users, a safer road network and the achievement of higher standards of connectivity with the rest of the transportation modes.

Spain is a country with a vast experience in the construction and maintenance of infrastructures; it is recognized as a leader in technology, quality, efficiency and management of roads. Over the last 30 years, the development of one of the most extensive highway network in Europe is a proof of its capacity. It counts on more than 14,700 km long overcoming a challenging orography and showing an absolute respect for the environment.

The 17th IRF World Meeting provides Spain with an incomparable opportunity to show our technical capacities and success stories to the international stakeholders. In addition, it is an excellent opportunity to foster the cooperation and networking of both Spanish companies and experienced professionals, to whom we owe the high-end quality of our infrastructures. The long-term goal is that they keep contributing to the development and improvement of road infrastructures all over the world.
Firstly I would like to thank the Spanish Road Association for their kind invitation to participate in the special edition of its Carreteras magazine dedicated to the 17th International Road Federation World Congress, that takes place in Riyadh, Saudi Arabia. During this event, the Spanish industry will display the high scientific and technological level reached to the international road community. It is mandatory reminding the importance and priority of this area for the national economy, having achieved notable successes over the last few years. At the same time, the Spanish Government has worked along this policy. The Ministry of Home Affairs, concerned about accidents and understanding every single death as a tragedy, has also made a great progress in order to ensure the safety of road users.

Figures, occasionally more eloquent than words, indicate that we are on the right track. The lowering of the number of deaths in road accidents in the recent years has been of high significance. The total road fatalities in 2012 (1,304), is roughly the same figure registered in 1960, when 1,300 people died on our roads. This number is even more significant if we consider that 52 years ago there were only one million vehicles in the Spanish roads, while today the figures sum up to 32 million. Furthermore, death toll has been continuously dwindling during the last nine years. During 2012, there were 2,937 fewer fatalities than in 2000, when there were 4,241 fatalities. Consequently, the average daily number of killed has improved from 11.6 per day (in 2000) to 3.6 in 2012. Summarizing, 8 fewer deaths every day.

Although these data clearly mark a positive trend, they are not a reason for complacency. On the contrary, they are an incentive to keep on working hard to find new ways of enhancing the safety of all road users. With this objective in mind, last July I promoted the reform of the Traffic and Road Safety Act in the Council of Ministers, which was approved. Changes are relevant, as they will allow the adaptation of the law to drivers’ needs, but also to the changes of vehicles and roads, determining key factors of accidents.

There are several sectors and stakeholders highly responsible for road safety; together, we must ensure that roads are not identified with accidents anymore. Roads are ways for communication, infrastructures that create wealth, progress and welfare for citizens, not places where people can lose their lives. For all the above reasons, the Ministry of Home Affairs will continue working with tenacity and perseverance to ensure that the current descent in the death toll is maintained in the long-term.
Twenty years ago Spain organised the 12th World Congress of the International Road Federation (IRF) in Madrid.

Although the Congress was held in springtime (May 1993) there was no way of knowing that it would be the harbinger of a burst of growth and a sustained line of action by the Spanish Road Association (Asociación Española de la Carretera, AEC) on the international scene. This line of action fulfilled its early promise towards the end of the decade with the foundation of the European Road Federation (ERF), in which AEC played a leading role.

The challenge of the European market, the natural habitat of the Spanish road industry represented by AEC, would later be extended to the Latin American and Caribbean region where the Association took a leading role in the institutional representation of the sector with the foundation of the Ibero-American Road Institute (Instituto Vial Iberoamericano, IVA) back in 2005.

The commitment to internationalisation of the activities inherent in the Association have taken shape and acquired momentum over these twenty years during which Spanish road infrastructures received the most potent boost in their history, helping to transform the country, its territory, its landforms and above all the concepts of progress and welfare.

Embarked on the mission of bringing a comprehensive vision and balance to the interests involved in this national modernisation process, the AEC also took up the parallel challenge of transmitting the technology that was being developed and implemented in Spain with startling success and efficiency to Europe, Latin America and the rest of the world.

No country can progress as quickly and consistently as Spain has done in recent decades if it is not backed by an excellent road network. And the sector's benchmark technical journal has always fostered this development and that of the companies and public authorities who made it possible. The journal you have in your hands: CARRETERAS.

This special issue of Carreteras could well be a symbol of the engineering and technological advances that have given rise to the great transformation of the road network in our country in recent times. It has been specially conceived and produced for the Riyadh World Congress, and was made possible by the inestimable contribution of many of the most distinguished university professors related to the road infrastructure sector in Spain.

In these pages you will find a clear and highly didactic distillation of the essence of many of the key aspects that have enabled this giddying transformation of the roadway grid in Spain. This issue covers everything from the most significant technical and regulatory aspects through the public authority structure that sustains them to the sensitivity of a decision-making process that ensures optimum environmental integration, not forgetting aspects related to the continuous improvement of road safety.

It also considers the financial structures that have been instrumental in achieving these objectives, the technologies adapted to optimised traffic management and many of the outstanding bridges and viaducts built during the decades under study.

All the above makes this edition of Carreteras an authentic vademecum of technical and construction solutions that can undoubtedly help to guide the development of the road network of a country.

Today, in Riyadh and in many other places all over the world where Spain can contribute its vast experience, we are proud to present this journal as a sample of the well-managed development of Spain’s current road network. I hope you enjoy it.
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Sculptural bridges: epic structures

José Luis MANZANARES JAPÓN
Doctor of Civil Engineering

ABSTRACT

Bridges have an inevitable impact on the landscape. They are an opportunity to create sculptures to communicate feelings, ideas and evocations to the onlooker. Engineers who are aware of this opportunity for transcendence give a new dimension to their structures and to their profession’s role in society.

Key words: Bridge, Landscape, Structure, Design

Sculptural bridges?

A debate has been raging for years among specialists on thoroughfares in the landscape, normally centred on three questions: do bridges have a favourable impact on the landscape, or are they cumbersome objects that disfigure and degrade the natural environment? Is it preferable to seek simple, merely functional forms to be just put up with and to go all but unnoticed, or, by contrast, should the reality of their impact be addressed with a sense of responsibility for enhancing the vista in which they are sited? And are bridges structures which as such owe their shape merely to load-bearing design, or may they also be regarded as sculptures?

Experience shows that in recent decades all bridge designers have to some extent accepted a reality which previously escaped them, namely that bridges are key features in an anthropic landscape. They are not just structures and may in most cases also be seen as sculptures.

They are huge objects; they have such a visual impact on their surroundings that they inevitably attract our gaze; they take centre stage; they constitute landscape (or cityscape) in themselves; they never go unnoticed and always arouse a mix of sensations in onlookers: wonder, admiration, aversion, hostility... Whatever the designer’s intentions, a bridge becomes a landmark, part of public heritage, a legacy for future generations and an urban monument, if sited in a city.

Any figure that is sculpted, modelled or erected in a human habitat as a public landmark may be seen as a sculpture. Even a building whose outer form attracts the eye and stands out from the urban fabric may be seen as a building-sculpture. What type of sculpture it is and what standing it deserves is another matter.

A concern for the aesthetics of bridges has long existed. In the late 19th century there was already a debate over engineers’ ability to satisfactorily deal with the question of beauty in their work and the need for partnership with architects in order to achieve it. Eiffel took a strong line on this, asserting that: “Because we are engineers, people think we are unconcerned about beauty in our structures and that though we build them solidly and durably we do not seek to give them elegance. But are not the true functions of strength always in accordance with the secret principles of harmony?”

In our view the great French engineer was mistaken, for static mechanics are not always fine-looking. But much of the education of structural engineers has been informed by that assertion, and so their aesthetic concerns have tended to be confined to a small, purely structural sphere, with any use of non-resistant add-ons being seen as contamination. Hence the traditional 20th century approach of conceiving of bridges as mere structures. The image they portray is a mere product of the load-bearing members of which they consist, the function they are to perform, the nature of their physical setting and the construction method used to build them.
This is surely a limiting and impoverishing notion. With globalisation, an understanding of structural calculations and construction systems has spread around the world. It is in anyone’s reach. Thus one finds similar if not identical bridges in places with disparate cultures, landscapes and peoples. This standardisation of form turns them into objects in a catalogue, not intended to stand out.

Seen from this perspective, for most of today’s top bridge designers a bridge is stateless, alien to race, fashion, culture and environment. When designing their bridges they conceive of them primarily as structures for performing a function, liable to be built at minimal expense. They may also like them to be beautiful, but they rarely go so far as to think of them as forms of expression.

For here is the key to the structure-sculpture dichotomy. A sculptor making a work of art does not set herself the task of making it beautiful. Aesthetics are not the raison d’être of sculpture. The sculptor wants her work to express feeling, to convey sensations, and she uses it to engage with the onlooker. The sculptural creation process is similar to that for composing a symphony, writing a novel or painting a picture. It is like a realisation of the creator’s soul, offering the rest of us and posterity a crystallised piece of her inner self.

Those who conceive of their designs only in structural terms do not set out to create sculpture – artistic objects intended to express emotion and convey it to an onlooker. The problem is, however, that though they did not set out to do so, sculptures are what they are creating. Soulless, for sure, for they are not meant to express feelings or ideas. They are children conceived with no transcendent intention by parents nonetheless wishing to perpetuate themselves in them.

This way of conceiving of bridges with no awareness of their sculptural role has another drawback from the engineer’s viewpoint, namely the lack of authorship. Just as a sculpture cannot be dissociated from the mind that conceived it, visual objects treated as items in a catalogue are, by contrast, orphans, with no parents perceptible to the general public. When engineers design a bridge with no sculptural intent they are at the same time renouncing the public presence they might have had as designers.

This depersonalising of a structure, cutting it off from any message, creator or ethnicity and shutting it in its role as a load-bearing edifice, taking no advantage of its nature as a big visual object, is parallel to its anonymity. If a structure is not linked to a designer seeking to communicate feeling through it, that designer will remain unknown. The structure will be an unsigned object and as such of little value, for nowadays value is attached only to artistic or intellectual expression bearing a signature.

We should be aware that this may be one reason why technical practitioners lack social prestige. No one outside the industry would if questioned be able to cite names of illustrious engineers, and this is why their works struggle to compete with architectural creations which do have that essential quality known as their “own style”.

Architects are well aware of their work’s role as a form of communication between designer and onlooker, known as the “semantic” aspect of their buildings. A structure must not be just functional, resilient and cost-effective; it must convey a message, communicate feeling, arouse sensations and, to this end, employ a discourse. And this conception of their work establishes a dialogue between society and designer that naturally gives them publicity and celebrity. Anyone could cite a list of celebrated architects and the reason for this lies in their desire to communicate through their works, which is what gives them the social prominence that engineers lack.

Engineers’ loss of social standing is clearly perceptible, and in today’s world a forgotten or ignored group is evidently in a bad way. Accordingly engineers should strive to recover the public role they had in the past, and to do this perhaps the only way is to reflect on the
mistakes made and propose a remedy.

We should start by asking, in the case of bridges, if their designers are on the right track, or if the obtuse notion of a solely functional role for such structures helps leave them in social oblivion. For they can hardly gain public recognition if in their works they fail to provide what society demands and instead confine themselves to what they think suitable.

Ethically speaking, prominence for engineers may be desirable for the engineering community, but this cannot be the sole motivation for making bridges to enhance the landscape as sculptural objects. Society is entitled to a finely crafted anthropic landscape, designed with transcendent intent. For this it needs designers with souls. And this relationship, beneficial for both parties, should be driven only by the urge to configure scenic landscapes adorned with structures designed by sentient creators with artistic intent. We should not forget that the desire to gain renown may lead us to fill the landscape with eyesores just to get public attention, as has unfortunately quite often occurred.

**THE BASIS OF A DESIGN**

The engineer’s conception of the creative process has traditionally rested on two pillars: function and economy. All that is designed and built must serve to carry out the purpose for which it was created. And it must have a reasonable, if not necessarily minimal, price. Thus a bridge’s purpose is to withstand the weights and loads it will have to bear, and it must without fail be on budget. Thus it is designed within a construction system in which anything superfluous is left out.

Though in recent years bridges’ image as artistic objects has begun to be taken seriously by designers, this has always been subordinate to those two pillars. With rare exceptions, any conveying of a message to society through a designer’s expressive faculty has been practically ignored in the creative process. Old-school engineers confine themselves to designing an object that is functional and structurally correct, and expect recognition for this.

Paradoxically society does not rate functionality very highly. The public takes for granted that engineering structures will work properly. Their performing of their function is seen as a matter of course, no more than an obligation met. Anything dysfunctional is seen as botched. No child is amazed when a plane flies or phone messages reach their recipients or television gives us a real-time window onto the other side of the world. It occurs to no one that the technician creating these marvels, or installing or servicing them, should have any special standing. They’re doing their job and that’s what they’re paid for. And if they get it wrong they can watch out and expect to be held to account. A bridge being built without mishap, staying up in the air, not collapsing and being easy to cross is what the public expects, not a feat deserving plaudits.

This working at minimal cost is another feature worth noting. Modern civil engineering came into being in the 19th century in a near-medieval Europe of hunger, cholera and social injustice. Those early engineers faced the task of structuring a territory with no infrastructure and had to wrack their brains to build with scant materials and funds. Hence the obsession with building structures at minimal cost that has driven and honoured the profession. The world has been filled with austere, effective constructions with no concessions to the landscape or to aesthetics. While no one would have thought of making buildings with no frontage or fancy trimmings with fine materials to embellish our cities, bridges were built with absolute economy of aesthetic resources.
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Why is this old system that gave us so many feats of engineering now out of date? Society around the world is very different today. Though much of the first world is in an economic crisis that is holding down investment in infrastructure, in the world’s thriving economies there is a desire to draw level with the most advanced societies, to organise their territory by fitting it out with engineering structures of the first rank. The value scale of citizens in developed countries generally aims upwards, and though they favour austerity they would not take it to extremes. Enriching the landscape and giving it dignity is a universal aspiration. So the priorities in structural design must naturally adapt to a new era.

A good example of this new perspective is the superb range of bridges built in Spain following the civil war. For as the country was being rebuilt and modernised with scarce means and much ingenuity, the need to conserve the exquisite anthropic landscape bequeathed by history was not overlooked. Faced with such a challenge, the civil engineers of the time excelled themselves in their philosophy of building new structures, for unlike in other countries, a sensitivity to the beauty of historical and artistic heritage was reflected in the care taken over public works.

As its landscape and cityscape are developed, society has little regard for engineers’ efforts to keep down costs, for the public perceives that when the services of technical practitioners are called upon, they work not for them but for the firms carrying out the building. People know that when we speak of a structure with optimal cost, we refer not to lower cost for society but to greater profit for builders. Thus this endeavour has little social impact. Anyone who knows the name of the construction firm which built a structure supposes that the thing is well built and that the firm made a profit, but is not interested in the engineers who made it possible or their role in managing its cost. They see them as equivalent to the anonymous types who design TV sets, cars or phones.

This public indifference and anonymity is largely a fruit of engineers’ education, in which they are taught that their work belongs to a team and that it is presumptuous to attribute its paternity to a single designer. Engineering schools have unremittingly condemned the narcissism of architects who claim sole authorship for work in which several practitioners had a hand. Moreover engineers have long accepted without complaint that their structures belong to the politician who commissioned or inaugurated them or to the construction firm. And this has put them so far out of society’s sight that it not only fails to appreciate their work but also ignores it.

Engineers who let function and cost be the sole basis of a project assume the role of anonymous servants of society and so miss the chance to leave a slice of human soul in the landscape.

**THE IMAGE-DOMINATED SOCIETY**

For today’s society, images are as vital as function or economy. What technology can do is now taken for granted. No one is surprised when a car keeps running instead of breaking down. No one would admire a vehicle for being able to brake, for evidently it needs to do so, and moreover everyone knows that competition will automatically control prices. The factor that determines how a product is ultimately rated is without a doubt its image.

Today’s developed world is far distant from that 19th century world in which the chief concern was subsistence. For the public, image, landscape and beauty have become vital sources of collective satisfaction. And bridges are so conspicuous – a lot more so than works of architecture – that their aesthetic impact is enormous. Like it or not, they have a vital influence on the landscape.
much so that one may almost believe, when designing, that engineers have the weighty responsibility of sharing with God the task of modelling the planet so as to make it more hospitable to the human race, both functionally and aesthetically.

Any impact on the landscape sets off a storm of popular feeling: horror, excitement, perceptions of beauty or harmony, indifference, sadness, enthusiasm... So when a bridge is designed, its image, consciously or unconsciously, sends a stream of messages to future onlookers. It is as if a great book were being written with huge pages conveying to society the sensations that the designer intended.

Onlookers and users of bridges, present and future, will judge them as visual features, and, taking for granted that functional issues have been resolved, will wish them not only not to clash with their surroundings but to ennoble and enhance them. And crucially society is willing to pay for this desire to be satisfied. Each structure built should cost as little as possible, but one item in its budget, naturally not overpriced, should be for the creation of its image.

Despite this reality, many engineers are fearful of the importance attached to form. This may be because a sector of society, not a majority but certainly a voluble one, has so denounced the assaults on the landscape by public works built for function and economy and with no feeling for imagery that they call into question any new construction. By so often disregarding beauty we have not only lost standing but also generated a general hostility to the impact of large structures.

Given the adverse reactions prompted by so many ill-considered bridges, many people, organised in influential groups, would have no more built. But as this stance is incompatible with development, many others put forward the apparently infallible rule that new constructions should be made to be inconspicuous. It is as if the best image for an engineering structure were invisibility.

And as there is no recipe for this, it is often concluded that it is the simplest possible structure that has least impact on the landscape. Yet this is not so, for the structures in question are so weighty and on such a scale that vulgarity, rather than blending them into their surroundings, impoverishes them.

Also, seeking to prevent anyone from altering the natural landscape is a battle lost in advance. Population growth and our growing needs require large-scale works which, like it or not, alter our perception - human in any event - of our natural environment. Landscape has meaning only through human eyes. So as we know what we build will inevitably be conspicuous, let us make it beautiful. And if we know it will arouse feeling, let us use it as a form of visual expression.

What is to be done

From these provocative reflections we reach the conclusion that sculptural concepts should be introduced into bridges in response to the dominance of imagery in today’s society. Hard as it may be to accept, bridges are huge architectural objects, portraying an image, creating landscapes and conveying feeling to the onlooker. And either we take seriously the task of consciously factoring in this aspect of our bridges or they will end up in the hands of other professions, which will see to their appearance and have anonymous engineers to do the job of erecting load-bearing structures.

The world of imagery is a difficult and alien one for engineers. One has to learn to live with criticism, envy, trends, fashions and cults. Often one has to take sides so as to feel backed by principles and rules justifying a form of expression. And above all one has to cast off anonymity. Engineers have sought anonymity voluntarily for centuries under the cover of construction and consultant firms.
In technical schools we are wrongly taught that modesty is a virtue. Yet society today prefers a work with an author to one that is anonymous. Is not the signing of a work of art, if the author is celebrated, worth as much as the creation itself? Architecture's unqualified supremacy in its professional rivalry with engineering lies precisely in its social prominence. Anonymity gives rise only to a disregard for one's work. What a mistake we make with all this modesty and depersonalisation! Any architecture student can cite twenty famous architects. Could the same be said of engineering students? Top architects appear every day in magazines and elsewhere in the media, where bridge-makers do not even exist.

We must urgently put an end to this oblivion, and to do so we need to spawn a new class of engineers. Good professionals, fired with the rigour and learning they have always shown but willing to seek the limelight, interested in engaging through their work with society, giving society what it demands: honesty, technical quality and formal quality.

**Elements of form**

And now the big question. If a bridge may be treated as a sculpture, should bridge-designers be confined to merely resistant materials or may they also include ornamental ones. What or who stops them from doing so?

This question was answered by pre-19th century bridge-builders, who clad their structures with expressiveness and harmony. In doing so they did not hesitate to include architectural features in their designs. Without fear of contaminating the structural function of their arches, lintels and piers they made free use of sculpture, frieze, relief, cladding, towers and gates so as to create an urban monument that would enrich the host city. The Rialto in Venice or the Pont Valentré at Cahors or the Ponte Vecchio in Florence are well-known examples. So what caused a formal notion that was widespread a hundred years ago to be lost?

When engineers discovered concrete and steel, these burst into expressive construction, bringing a new discourse. The beauty of a pure, well-proportioned structure with a clear load-carrying mechanism, especially when audacious, allows one to dispense with the extra features which previously had to be made use of to create beauty and arouse emotion. Pleased with these new materials, designers forsook all else that might clad or conceal their bold and novel constructions, which were flabbergasting structural feats.

Throughout the 20th century, exquisite bridges were built with no means other than structural ones. Formal concessions were confined to the guide-lines and cross-sections of load-bearing features and the result in many cases was so spectacular that no one now dreamed of making superb new bridges like the Pont Alexandre III in Paris, with its incredible segmental arch adorned with cast-iron garlands and columns with angels on the abutments.

In the early 21st century, some still aspire to bare structure as their sole means of expression. And it is true that this still offers a magnificent solution for wide-span bridges. A gigantic structure will stand out for its pure lines, its audacious slenderness or its fine structural materials. But with short and medium-span bridges, this approach has questionable results.

There are bridges with forty-metre spans that could have been made with four standard beams, but ill-conceived...
aesthetic urges turned them into gruesome contraptions exhibiting a crazy panoply of structural resources suited to big bridges but silly on small ones such as cables, stays, tilted arches, etc. Engineers are appalled at the idea of using cladding or ornaments but do not blush on adding unnecessary and showy load-bearing features.

This exclusive limitation to structural elements leads an engineer seeking an original design to employ means unjustified by the loads to be carried but which have the look of mechanical virtuosity. What anguish is felt by engineers charged with producing a noteworthy structure with resistant materials only, when, as often, the laws of static mechanics point to a vulgar solution! Why should they not be allowed to use other not necessarily structural materials to make an object of beauty?

A bridge should function as a connection for traffic, it should durably withstand loads, it should have a reasonable cost, i.e. it should be viable to build, and it should be a beautiful, outstanding feature in the landscape, speaking a language intelligible to the human soul. To achieve this the designing engineer may call on whatever comes to mind: structure, form, cladding, sculpture, colour, buildings, etc. All that need be asked in return is imagination, creativity, sensitivity and, naturally, a step into the limelight. Society, that implacable judge of beauty, will then bless or condemn the creation.

**Epic Structures**

All these reflections have been key to the way in which the firm AYESA has approached the design of urban bridges. Questions arise: With what guidelines? And, with which aesthetic tendencies?

As the doctrine we have described allows for a thousand and one varieties of design, it is up to each designer to find her way, either as part of a visual arts movement or alone. Aesthetics in a structure can be interpreted in many ways and each engineer or team of engineers will make an interpretation according to their tastes, character or approach to life.

When designing a structure a designer may prefer to forge a new style or to go along with one of the myriad trends and fashions in design. Architects follow trends, join movements and sign up to styles as if they were religions. But the world of engineering structures is less systematised.

Post-modernism and minimalism have tended to eliminate formal expression from structures, which are either bashfully concealed or left to go unnoticed with their austere straight lines, grey concrete or blue Corten steel.

Santiago Calatrava uses structure as a sculptural element. He sculpts his giant forms, animal or vegetable, as structural meshes of tapering white members that appear to have a load-bearing function which in most cases is no such thing. Certainly he has supporters and detractors, but he has shaken up the field of structural imagery and won an indisputable place on the world stage. We should not forget that controversy is inherent to architecture.

In his shadow many imitators have emerged, putting up gigantic structures with technological frills, girders, cables, turnbuckles, columns, braces, etc., forming
complex contrivances that seem to have a structural function but which really are supernumerary and for effect, not for providing a functional, elegant solution free of superfluous resistant materials.

Calatrava takes advantage of each assignment to erect a sculpture that will serve as a bridge. In his wake, notable engineers such as Manterola have followed on the path of using load-bearing elements to produce elegant forms in space and have achieved this with no need to renounce Torroja’s structural precepts. Though they shun concessions to imagery beyond gracefully slender resistant materials, other elements are increasingly being included in a clear attempt at providing an object of beauty.

On the realm of urban bridges there is little more to be said. This field has barely been touched by the recent upheaval of form for form’s sake in architecture, with unstructured expression, amorphous volume and low-grade surfaces that seem demented more than anything but which are now enjoying an undeniable success. The first experiment in this line was the Bridge Pavilion at the Zaragoza Expo with the winning design by Zaha Hadid and that submitted by the author of this article, with less success than his Iranian colleague.

Now I will confess that I have always had an independent bent and have preferred to find my own way rather than follow in others’ footsteps. In keeping with this I have set out on a new path with my team which has led us to a personal way of conceiving of urban structures. Our designs have a peculiar genesis spawning a range of solutions which we call “epic structures”.

The idea that a bridge may express and convey sensations will necessarily manifest itself differently in each designer. The need to express our inner selves through design is as diverse as the range of characters and intellectual aspirations to be found in a profession. In our case a liking for the epic, for telling stories and for recounting legends like minstrels has marked our way of conceiving bridges. If we regard everything as epic, we cannot help but transcribe onto paper the stories that life offers or suggests before our eyes. And as stories conceived in the imagination are written down, existence itself may be turned into stories.

Well then, can this spirit of those who create stories on paper be transferred to structures? If our work has a discourse, a semantics serving to convey feeling to the onlooker, can it not tell a story? So one day – how is hard to say – the answer to this question took shape: we set about designing epic structures. Structures whose form is dictated by a poetic story emerging in the creator’s mind in unison with the design.

A bridge, and especially an urban bridge, is always monumental, because of its dimensions, bigger than those of other constructions in the vicinity, and also because it is a structure of a historical kind, linked to a certain period together with its tastes and customs. But it may also take on monumental status in the light of the third meaning that the Spanish Royal Academy gives to the word monumento: a prominent public structure erected to commemorate something remarkable.

Many bridges come under this third category when they are named. Their names commemorating kings, anniversaries or great figures make them monumental tributes. But the reason for which they are named rarely feeds into their design. Though in sculpture the subject of homage is normally reflected in the image, in bridges, functionality, if not a lack of interest on the part of designers in making such a formal link, dissociates form and name.

It is reasonable for a designer to feel that a new bridge should be informed by the city or landscape in which it is located – by its marks of identity, and should be a monumental and morphological statement in tune with local history and culture. This aim may be achieved in two ways: taking formal elements from the cityscape that characterise its architectural styles, or forging a new image based on a story unequivocally representing a genuine spiritual facet of the place, given palpable shape in a structural design. It is in this latter approach that the “epic structure” concept arises.
The epic is present in all forms of spiritual expression: since the epic genre of the Greeks it has been part of literature, characterising poetry or the theatre and also extending to music, painting, sculpture and – why not – architecture. As opposed to the lyrical paintings of a Matisse, with his fickle and indolent dancers like branches bending to the rhythm of the music, the epic Picasso of Guernica speaks of death, war and bombings. There is also an epic architecture when what goes on inside a building is reflected in its outer form.

Why should we not also conceive of an epic structure? A bridge whose form takes shape along the lines of a story, in the image of an epic saga, gives its justifying narrative form in a monument. The notion is viable, though plainly not without risk, for a material expression of literature runs the risk of being over-literal.

When an engineer writes stories and perceives existence as if it were a novel, the idea is tempting, and it is hard to resist the appeal of giving the story concrete form, not just in sentences but also in concrete and steel.

An epic bridge is nothing other than a structure whose form is inspired by a literary, historical or imagined story linked to the place and landscape, a suggestive exhibit for future generations.

As in all things, there will be fine epic structures and others that are grotesque or half-baked. They will have supporters and detractors. Minimalists will certainly repudiate such a concession to imagery, but in the field of structural semantics you have to live with controversy, debate, support and hostility. And to avoid the risk of tending to the baroque, we must keep intact a respect for clear, limpid structures with no superfluous load-bearing elements.

Epic structures may include concessions to form, colour or cladding and also ornamental features in their design, but they must work well as structures, and be economically viable.

At AYESA in recent years we have designed several epic bridges. Some have been built and have given us the satisfaction of being well received by the public. Some have not won the tenders to which they were presented. But in all of them we have enjoyed materialising in a design
Más de cincuenta años construyendo futuro.

Over fifty years building the future.

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something that moved us – at the end of the day, the raison d’être of creative endeavour.

**Epic bridges**

As examples of epic bridges, in this paper we will show three designs.

The first is a bridge over a motorway in Tenerife. It gives access to a wind farm for which a design competition was held with a view to providing a landmark that would constitute an image for the facility, and to which the best in the profession submitted entries. The jury selected our proposal.

The bridge represents the story of Atlantians who sailed to the island on rafts with sails in search of the Garden of the Hesperides. Teide, a mythological dragon, defended the island from its assailants by spraying them with lava. Their petrified remains are still to be seen in the lunar park of Granadilla, where the structure is built.

A vertical plate holds in place a slender deck in a reinforced concrete bridge with a simple load-bearing profile and a cost suited to what was wanted by the park owners. Today it is seen as one of the island’s chief tourist attractions.

Our second example is a bridge in Alcalá de Guadaíra, a handsome town near Seville. The planning authorities decided to build a road bridge below an Almohad castle, the town’s iconic landmark, across a bucolic riverside park. The environmental sensibilities of local stakeholders led the suitability of such a large structure in such a spot to be questioned. So they held a design competition to choose the solution with least impact and most liable to win public approval.

We thought the only answer was to build a city park attraction which would also serve as a bridge. In public parks one finds fountains, sculptures, benches, swings and slides and all manner of objects to contribute to recreation. The solution we proposed was to build a giant mythological creature with iridescent, multicoloured skin, rooted in the history of the place. It was designed to stimulate the imagination of children playing near it and to constitute a pleasing scene that would live up to such an attractive site.

For the design we drew upon the legend of a dragon that saved the son of Caliph Abu Yaqub Ben Yusuf from an attack by the Almoravids and helped his royal party to cross the river Guadaira. The idea of making a figurative bridge seemed extravagant from the perspective of merely functional engineering, but our aim was quite different: to produce a sculpture that would serve as a bridge.

Today the Dragon Bridge, which has started a trend, is a source of pride for local people, a must-see for tourists, a centre for local festivities and permanent food for the imagination of children playing near it.

The third example is a larger bridge over the Guadalquivir in Cordoba, which pays tribute the 9th century engineer Abbas Ibn Firmas.

The responsibility of building a large bridge on the outskirts of the city meant that a monumental component had to be included in the design. A great city is configured over history by the monuments that various generations leave in its cityscape. A bridge over the river that flows through it cannot fail to be monumental, and its designer must seek to create a piece of heritage as required by such a site.

Urban bridges are normally erected in honour of some prominent figure and named after a king, prince or hero linked to the city. Yet there is normally no formal link between the subject of the tribute and the structure, or it is confined to a sculpture or engraving with an image of the eponymous person. In this case we decided to make a design to commemorate the caliphate of
Cordoba, the 9th century capital of the world, in the person of one of its great men.

The city of Cordoba was noted for its intellectual role and its ability to irradiate culture from its walls to the rest of the world. Its libraries, poets and sages formed a beacon that enlightened a world benighted in medieval darkness. Its most remarkable figure was an engineer, mathematician and scientist of Berber descent who made an untold contribution to contemporary learning.

Abbas Ibn Firnas, pioneer crystallographer, inventor of the mechanical clock and creator of planispheres, was also the father of aviation. He devised a theory of flight which he was bold enough to demonstrate by jumping with feather wings off the tower of La Rusafa. To the amazement of his peers, he survived. His feat is acknowledged by every university, a professorship in Houston and a room at the Moscow Science Museum that has been named after him.

Our bridge, with two three-dimensional arches simulating giant wings, has at its centre an abstract representation of the man who made that giant leap for humanity. It is an epic structure whose form recounts the exploit of the first human flight.

**Postscript**

The way to build bridges with identity, as a form of expressing creativity, is to make the engineer who designs them a public figure, via a long process strewn with obstacles. It is a challenge involving the difficulty of bringing about a change of collective mindset. We need to arouse an artistic sensibility in students, a desire for culture, a social awareness and a wish to emerge from anonymity. We also need to encourage designers to throw off their shyness, to let out their feelings and to step into the public arena as creators who have something to say.

It is an arduous task. But if anything characterises the profession of bridge-builders it is their supreme capacity for solving problems and meeting challenges. I’m convinced that the goal is clear and that we need only find a way. But then that’s something that we’re experts at...

**Bibliographic references**

Managing motorways for improving energy efficiency

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Natalia SOBRINO
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ABSTRACT

Transport climate change impacts have become a worldwide concern. Transport is responsible for 41% of CO₂ emissions in Spain, and around 65% of that figure is due to road traffic. Tolled motorways are currently managed according to economic criteria: minimizing operational costs and maximizing revenues from tolls. Within this framework, this paper develops a new methodology for managing motorways based on a target of maximum energy efficiency. It includes technological and demand-driven policies, which are applied to two case studies. Various conclusions emerge from this study. The results clearly indicate that to achieve the best carbon footprint savings it is necessary to design sustainable strategies to manage each motorway section. That means to use the maximum of its capacity according to the total traffic flows of cars and heavy duty vehicles in the motorway road and also in the parallel roads. Another important finding is that substantial GHG reduction emissions could be achieved in the toll plazas with the application of Electronic Toll Collection (ETC) and Open Road Tolling (ORT) schemes.

Key words: Energy efficiency, Traffic flow management, Toll gate operation.

INTRODUCTION

Transport is widely recognized to be one of the most significant sources of greenhouse gas (GHG) emissions -in particular CO₂ emissions- which are directly related to the consumption of carbon-based fuel. The transport sector provides economic and social benefits to society as a whole, and yet it causes a number of negative environmental impacts. A significant share of world CO₂ emissions is produced by the transport sector, accounting for 23% of overall CO₂ emissions from fuel combustion and 15% of overall greenhouse gas (GHG) emissions at a global level (ITF/OCDE, 2010[5]). Road transportation represents the bulk of transport emissions, some 75% worldwide (IEA, 2009[4]). In Spain, increasing transportation demand – especially for road-based modes – is the main reason for the rise in GHG emissions (Mendiluce et al, 2011[6]). From 1990 to 2009, road traffic volume in Spain has increased by 94%, consequently, GHG emissions from road transportation have risen by 65% in that period (Ministerio de Fomento, 2011[3]). Countries are increasing their energy dependency, and consequently their impacts on not only the environment but also on the economy: oil prices, taxes, external costs, etc. For this reason, and to comply with the Kyoto Protocol target of reducing GHGs emissions to 1990 levels, numerous policies have been implemented at both the national and international level which are designed to reduce energy
consumption in the road transport sector by acting both on the planning and operational side. In addition to continuing to encourage efforts in fuel efficiency standards, promotion of new efficient vehicles, eco-driving, behavior change to more efficient modes, etc., attention should be paid to road authorities and operators. They have the potential to manage the road network in a safe, reliable, economical and sustainable way. This last aspect - contributing more to sustainability and overall energy efficiency - must be taken into account in a new road management approach, specifically aiming to reduce energy consumption on the road network due to traffic flows.

A new effective management should be defined to help road authorities and stakeholders to optimize energy consumption and CO₂ impacts throughout the operational phase of the roads. Energy savings are still far from being part of the operation strategy of motorway networks. The main concerns for road managers are reducing costs and accidents, but reducing energy consumption is still not in their agenda, neither in the construction phase, nor in the operational one. On the other hand, the development of new and more efficient payment and control ITS systems provide new tools for better management with solutions that could be tailored for each specific case study.

This paper presents intend to show that another approach could be possible. It is possible to achieve significant benefits when applying energy efficiency strategies in managing arterial road networks. The paper is structured as follows: Section 2 deals with the estimation of the road footprint as a new approach to managing roads. Section 3 and 4 describe the main variables which should be considered for motorway footprint optimization in two selected GHG reduction strategies. Various policy applications are then validated in two different case studies.

Finally, some results are obtained which form the basis for proposing new strategies for reducing carbon emissions in motorways (Section 5).

Road footprint: a new approach for managing roads

The carbon footprint of a road can be defined as the total amount of CO₂ and other GHGs emitted over the full life cycle of a road (construction, operation, maintenance and deconstruction phase). However, this paper deals only with the road operation that manages traffic flows emitting CO₂ due to fuel combustion. Energy consumption and emissions models are used to estimate the road footprint in the operational phase. These models provide an objective tool to evaluate measures, strategies and scenarios and can integrate the management of the energy footprint, air quality and energy efficiency into the decision-making processes (Affum et al, 2003). Energy consumption -and consequently the CO₂ emissions- depends on a number of parameters such as road layout (type of road and gradient), its roughness, traffic flow distribution, congestion levels, etc. A large number of models have been developed for this purpose (Smit et al, 2010) considering road and traffic characteristics. Other models are based on applying the principles of mechanics to the calculation of energy consumption and emissions (Burgess&Choi, 2003; Janic, 2007; Zachariadis, Ntzichristos, & Samaras, 2000). They determine energy consumption in proportion to the forces that oppose vehicle motion, including rolling resistance, aerodynamic drag and air entrance resistance, and inertial and gravitational losses.

The total of CO₂ emissions from motorway traffic flows depends on different factors, as shown line A of the following figure. Carbon intensity depends on fuel efficiency standards, which are currently the most widely-used transport policy instrument for stimulating climate change mitigation and reducing oil dependency (Creutzig, et al 2011). Demand refers to the most rational use of the vehicle. Actions such as promoting eco-driving, modal shift to more efficient transport mode, etc., can control demand (Pérez-Martínez et al, 2011). Finally, consumption factors depend on speed, road gradient and vehicle type, which are the main input variables for calculating the road footprint (line B) and for managing the road (Monzon et al, 2012).
In order to optimize the road footprint, line C represents policy actions that influence total CO$_2$ emissions from traffic flows. Operators can act directly on these variables through strategies involving energy efficient road management. Recently, speed management has become a far more popular strategy for reducing road emissions as well as contributing to traffic safety (Int Panis, Broekx, & Liu, 2006; Keller et al., 2008; Keuken, Jonkers, Wilmink, & Wesseling, 2010). Road design plays an important role at the design and building stage, since road gradient is a direct variable. Encouraging vehicle fleet renovation is another way of promoting energy-efficient road transport (Aranda Uson et al, 2011). Finally, network management integrates all these actions and considers the combined use of all alternative O-D routes.

In order to show the energy savings potential, two different strategies are shown in this section. These case studies have been designed to provide a more integrated approach to reduce motorway footprint. They show two possible types of policy actions: speed and traffic control among different road alternatives, and to reduce congestion at toll plazas with the help of intelligent control systems.

**Case study 1: better use of toll motorway capacity**

In many countries toll roads are not used by HDV or car because the deterrent effect of paying a toll. This is clearer in the case of economic problems affecting either to some drivers or to specific countries suffering situations of economic crisis. This produce in turn clear problems to motorway concessionaires because the traffic is much less than the expected.

In order to analyze this problem we have selected an itinerary which has two alternatives roads: a conventional road (alternative 1) and a toll road (alternative 2). The scenario is then built taking into account three different types of management: traffic flows and speed management. The road footprint is calculated for each scenario, considering the total of the two alternative routes and directions. The next step is the comparison of the footprint scenarios. The reference scenario is compared to the different management proposals in order to evaluate the most energy-efficient management options. The different management strategies and scenarios are explained in Table 1.

This scheme was applied to analyze the case study of Pajares. Two parallel road alternatives that pass through the Cantabrian Mountains between Leon and Asturias in northern Spain. The first alternative corresponds to the N-630 conventional road; the stretch analyzed is a mountain pass which is relatively hilly and with strict speed restrictions, and has a total length of 76.8km. The second alternative is the AP-66 toll motorway. It has higher road quality than the N-630, since the hilly stretches are resolved by means of tunnel and viaducts. The total length of the study route is 77.3km. The data for the input variables are derived from the following sources: AADT and speed data are obtained from the Spanish Traffic Map 2009 (Ministerio de Fomento, 2009). The route division by stretches, road gradient, and length are obtained from the test conducted in March 2011 with on-board recording equipment.

The outcomes show that speed management strategies to be the most effective, along with the integration of traffic flows and speed management. Conversely, scenario S TOLL shows an increase in fuel and energy consumption and CO$_2$ emissions. This is justified by the fact that although toll motorways are better quality, their speed is greater compared to conventional roads, thus increasing the road footprint. The comparison of each scenario with the reference scenario S0 is shown in Fig.3. Under scenarios S SPEED↓ and S SPEED↓2, the

<table>
<thead>
<tr>
<th>MANAGEMENT STRATEGY</th>
<th>SCENARIO</th>
<th>DEFINITION</th>
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</thead>
<tbody>
<tr>
<td>Traffic management</td>
<td>S 0</td>
<td>Reference scenario</td>
</tr>
<tr>
<td></td>
<td>S TOLL</td>
<td>All traffic flows are transferred to the toll motorway.</td>
</tr>
<tr>
<td></td>
<td>S HDV</td>
<td>All heavy-duty vehicles for the conventional road are transferred to the toll motorway.</td>
</tr>
<tr>
<td>Speed management</td>
<td>S SPEED↓</td>
<td>-10km/h: speed reduction on the toll motorway for light vehicles</td>
</tr>
<tr>
<td></td>
<td>S SPEED↓2</td>
<td>-20km/h: Speed reduction on the toll motorway for light vehicles</td>
</tr>
<tr>
<td>Traffic + Speed management</td>
<td>S HDV+SPEED↓</td>
<td>heavy-duty vehicles are transferred to the toll motorway + speed reduction on the toll motorway for light vehicles (-10km/h)</td>
</tr>
<tr>
<td></td>
<td>S TOLL+SPEED↓</td>
<td>All traffic flows are transferred to the toll motorway + reduction on the toll motorway for light vehicles (-10km/h).</td>
</tr>
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</table>

Table 1. Proposed management strategies of two alternative roads.
Grupo Postigo’s LPT (Low Power Technology) Variable Message Signs (VMS) enhance road safety while addressing global ambitions towards saving energy and sustainability.

The technology exhibits a power consumption under 300 watts on a 64 x 64 VMS displaying a message using the greatest number of LEDs.

- Reduces power consumption by over 85%.
- Requires simple connections and minimal cabling.
- Cost saving in installation, operation and maintenance.
- Reduces CO₂ emissions.
- Option of using independent renewable energy supply.
- Provides high efficiency and prolongs the life of LEDs (100,000 hrs = 11 years).
- CE certification to European Standard EN12966 including recommendations for the selection of VMS meeting energy efficiency criteria.
greater the speed reduction, the greater the changes in emissions. A speed reduction of 20 km/h leads to saving of almost 5.5% of CO₂ emissions per year with regard to the reference scenario. Nevertheless, speed reduction leads to an increase in travel time. Transference of heavy-duty flows to toll motorways produces savings of less than 1%. However, transference of heavy-duty flows to toll motorways with a speed reduction for light vehicles on toll motorways produces emissions savings of nearly 4%. It should be noted that S HDV+Speed is the most energy-efficient scenario, although CO₂ emissions and fuel consumption are smaller than S Speed↓2. This is justified by the fact that HDV have been assumed to use only diesel fuel, which is more energy efficient than petrol.

**Case study 2: ITS contribution to reduce carbon footprint at tool plazas**

The following section deals with the management strategies which are proposed for the case study of toll plazas on the AP-6 motorway. The proposed methods for estimating CO₂ emissions at toll plazas are applied to several scenarios which considered different management strategies for optimizing the carbon footprint of toll plazas (Hernandez el al, 2013). The AP-6 corridor has been selected as a case study for testing the methodology proposed in this research. This toll motorway is located just northwest of Madrid, Spain. Its total length is 69.6 km, divided into three toll sections and two free sections. The test site included two main-line AP-6 toll plazas, San Rafael and Sanchidrian, located along the motorway at kilometer points 60.5 and 102.5 respectively.

Traffic volume data for the two toll plazas have been provided by the AP-6 toll motorway concessionaire, ABERTIS. Traffic volume differences between them are significant. San Rafael has an AADT of 16,043 veh/day, 21% of which is heavy vehicles, on working days, and 18,728 veh/day with 13% heavy vehicles, on non-working days. Traffic volume in Sanchidrián toll plaza is lower: on working days, its AADT is 8,095 veh/day, of which 13% are heavy vehicles, and on non-working days it is 10,209 veh/day with 5% heavy vehicles. It should be noted that heavy vehicles include rigid trucks, articulated trucks and buses; light vehicles are passenger cars, vans and motorcycles. Hourly traffic distribution is similar in both toll plazas, with two peak periods in an average day. In the case of light vehicles, traffic volume is about the same in the early hours of the morning. But from 11:00 am the traffic increment in San Rafael is higher than in Sanchidrián as is shown in Figure 4. Hourly traffic distribution of heavy vehicles is similar in both toll plazas.
higher in San Rafael especially at middle of the day.

The toll collection systems in both toll plazas include manual lanes and ETC lanes. In the current study, the manual collection systems include cash and card payment. As shown in Table 2, light vehicles generally use the manual toll systems, with a more than 85% share for working days and around 90% for non-working days. The heavy vehicles distribution by toll collection system is also very similar at both toll plazas; ETC lanes are used much more by heavy than light vehicles.

The suggested management strategies follow a scenario-building approach. Two different strategies have been proposed: toll collection systems management and queue management. The toll collection systems management strategy considers three different types of payment at both toll plazas. The current management situation is considered as a reference scenario to the three new ones: manual, ETC and ORT. The comparison to the reference scenario evaluates the increase or decrease in CO2 emissions. The methodology is applied to the scenarios on both working and non-working days. CO2 emissions in tons per day are determined by toll collection system with annual data from the AP-6 concessionaire, 2010. The CO2 savings results allow the proposed scenarios to be compared.

The findings reveal that the application of new toll collection technologies is an effective management strategy. ORT systems are particularly effective and can lead to CO2 emissions savings of up to 70%. This clearly justifies this type of toll system which eliminates barriers and collects electronic payments without affecting highway speed. The CO2 emissions savings achieved by ETC systems implementation come to more than 20%. In contrast, the maintenance of conventional toll booths as the only payment system supposes an increase in energy consumption and CO2 emissions. In fact, on working days, CO2 emissions were increased by almost 6% at the San Rafael toll plaza and by almost 5% at Sanchidrian. On non-working days, this increment is smaller at both toll plazas due to a decrease in the volume of heavy vehicles (about 3%). The comparison of each scenario with its respective reference scenario is shown in Table 3.

### Conclusions and recommendations

Energy efficiency is of key interest to transportation stakeholders. It improves global warming, health impacts and fossil fuels dependency. This paper states the potential of implementing different motorway management strategies and toll payment systems on energy consumption and CO2 emissions. An energy-efficient management approach was developed for the Spanish motorways, capable of addressing policy measures and strategies in different situations. Moreover, the methodology has been analyzed and validated by application to two different case studies. However, the procedure to manage traffic flows from the point of view of energy efficiency could be applied elsewhere in any road section of any country. The research has considered traffic flow efficiency by promoting energy-efficient alternative routes which could reduce energy consumption and emissions at very low

<table>
<thead>
<tr>
<th>Toll Collection System</th>
<th>Light Vehicles (%)</th>
<th>Heavy Vehicles (%)</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>San Rafael</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual</td>
<td>86</td>
<td>47</td>
<td>79</td>
</tr>
<tr>
<td>ETC</td>
<td>14</td>
<td>53</td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>82</td>
<td>18</td>
<td>100</td>
</tr>
<tr>
<td>Sanchidrian</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual</td>
<td>88</td>
<td>49</td>
<td>83</td>
</tr>
<tr>
<td>ETC</td>
<td>12</td>
<td>51</td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td>90</td>
<td>56</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 2.** Share of Toll Collection by Vehicle Type and Day of the Week, 2010.
Abrimos paso a nuevas ideas

¿Una carretera que descontamina el aire que respiramos? ¿Residuos domésticos reciclados en áridos para la carretera? ¿Pavimentos que en su fabricación ahorran energía y reducen la emisión de gases? ¿Pavimentos que absorben el ruido del tráfico? Hasta hace poco, estas ideas eran pura ficción. Actualmente ya tienen nombre: Noxer®, Tempera®, Viaphone®... y se utilizan diariamente con éxito. Para imaginar carreteras de mañana, creemos en las nuevas ideas, incluso en las más sorprendentes, por eso innovamos.

Probisa, una empresa de Eurovía
The case study revealed that the most effective traffic flow management is the reduction of speed on motorways for cars, which was also proved in the sensitivity analyses, with reduction of some 5.5% of CO2 emissions. Furthermore, heavy-duty vehicle flows have also been successfully transferred to alternative high-quality motorways, reducing energy consumption by 0.65%.

With regard to toll plaza management, it has been proved that the use of new technologies would reduce energy consumption and CO2 emissions up to 70% and improve other factors such as travel time. The assessment of different toll collection systems – manual, ETC and ORT– at toll plazas has proved the benefits of the most advanced systems both for saving energy and reducing congestion.

In conclusion, strategies for managing roads should look multiple targets, including a safety and less congestion, but also more sustainable use. This papers shows that all these targets are not contradictory if we consider integrated strategies for the whole motorway network.

**Acknowledgements**

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Innovative two-lane rural road safety geometric design process

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ABSTRACT

The traditional road design process starts with the selection of a design speed, which drivers are expected to prefer when driving along the road. This speed is used as a basis for several road parameters, hence its importance. But drivers are evidently unaware of this speed, and instead of keeping to it they drive at so-called operating speeds. This often leads to major road safety issues, even where a road segment complies with the applicable standards. This paper presents a new proposed methodology for road geometric design that considers operational and consistency criteria, with a view to building roads that better fit drivers’ expectations and which are therefore safer.

Keywords: Geometric design, Design speed, Operating speed, Consistency, Road safety

INTRODUCTION

1. The traditional geometric road design process

Geometric design is the major part of designing a road. Setting out from certain prior constraints, a definitive geometric layout is determined with a view to achieving the key goals of functionality, safety, comfort, environmental integration, harmony or aesthetics, economy and flexibility.

Though the end result is three-dimensional, it is not normally directly developed as such. Thus the traditional development process involves the iterative design of a three-dimensional model in which every part or projection is treated separately, but, in turn, the impact on the whole is assessed at each step, and the design is analysed for compliance with standards and the various criteria or goals.

We should also keep in mind that not all design aims will be in harmony, and some will even be in conflict. This impossibility of meeting all the aims at once leads to a need to prioritise some over others. Moreover the aim of achieving road safety has traditionally been confined to a mere compliance with applicable standards.
There are many factors or constraints in design, classifiable as external (or pre-existing) and internal (specific to the road and its design). Notable external factors are the relief of the terrain, geology and geotechnics, traffic demand, planning constraints and climate. Examples of internal factors are the different kinds of speed or the operational effects of geometry (sight distance, etc.).

The expected speed is perhaps the most significant parameter in the design process. Thus defining an initial speed on which to base a road design is a key question. This speed is known internationally as the “design speed”, and it is selected chiefly on the basis of the road class or type, the relief of the terrain and adjacent urban development.

This design speed is regarded as a starting point in defining the geometric controls applicable to the design of a road section. Thus the values for minimum sight distance, curve radius, transition parameters or cross-sections are defined according to that speed. The next step is geometric road design, in keeping with those controls and design standards.

**2. Dimensions of road safety**

One of the main goals in design is road safety. Many of the relevant standards and recommendations focus on this aspect, which should accordingly receive special attention in the design process. So establishing how road safety is considered in any road design becomes a major goal. The various ways of measuring this factor are known as “dimensions” of road safety: nominal safety, statutory safety, substantive safety and actual safety.

Nominal safety is determined by a design’s degree of compliance with the criteria and precepts in design guidelines and standards. Such guidelines include a series of parameters as thresholds, defining what is valid from the design perspective and what is not. These threshold values cover not only safety but also other design goals such as economy, environmental integration, etc. Consequently safety compliance in the nominal dimension does not mean that a road design is actually safe.

Within nominal safety we have “statutory safety”, which leaves in the driver’s sphere any responsibility for accidents due to infrastructure and its limitations. But complying with legal precepts does not necessarily assure any particular level of road safety, for many such precepts are intended just to limit financial repercussions.

Substantive safety, unlike the previous dimensions, is linked to the accident rate rather than to the design’s regulatory compliance. Thus it is linked to the number of accidents and their severity. In considering this dimension of safety we can estimate of the impact that a particular road design or upgrade may have on the accident rate through various previously calibrated methods. This dimension is of a continuous nature, allowing us to estimate the impact that altering a factor in design will have on accidents. It corresponds to a view of safety that is closer to the reality than the nominal and statutory dimensions, whose nature is discrete (a design is either safe or unsafe).

The need to properly consider the effects of geometric design has, especially in recent years, led to the development of methods and tools allowing the know-how obtained in experience and research to be drawn together and put to practical use. Thus any engineer can check their designs from the dimension of substantive safety, i.e. safety that is quantifiable, testable and comparable.

Finally actual safety is determined by the accident rate on a road network in service. An analysis of actual safety should feed into a search for effective local solutions, but broader, rigorous research into this also improves our understanding of safety with a view to providing better substantive safety.

The application of substantive safety, based on actual safety, may allow us to go beyond nominal safety and widen the scope of road design, including new concepts of flexibility and adaptation to the environment. It is vital to select suitable measures, compare alternatives and prioritise projects, quantifying and predicting behaviour with respect to the road safety of the various highway features\(^1\).
3. Speed concepts

As indicated above, the design speed is one of the key factors to be considered in road design. Historically the classic criterion has been to select and apply a design speed as defined and adopted in the US in 1936(II), assuming that all vehicles are going to travel steadily at that speed, according to the road type, orography and urban development. Applying it allows us to establish a minimum threshold for certain basic design parameters such as minimum curve radius and the sight distances required for certain manoeuvres.

But in fact drivers do not travel at a steady speed along a route but rather vary their speed according to the road conditions, especially geometric ones. This is why in the past two decades the classic concept has been reconsidered in certain countries, with a review of methods so as to take better account of the manifest disparities between design speed and operating speed, especially on rural roads.

Within the design speed concept we may differentiate two terms: designated design speed and inferred design speed(III).

Designated design speed is the speed used explicitly by an engineer to establish minimum values in geometric design, such as curve radii or sight distances. This concept is equivalent to the design speed defined in most guidelines.

Inferred design speed is applied only to characteristics and features that are determined according to criteria based on (designated) design speed. It is equivalent to calculating, for a certain geometric feature, the (designated) design speed that would be associated with it, even if that feature is not the most restrictive one in the homogenous section to which it belongs. This concept may be regarded as equivalent to the specific speed defined in the Spanish road layout standard.

Contrasting with design speed we have operating speed, which may be defined as the passenger cars at free-flow conditions without environmental restrictions, i.e. with the sole constraint of the road’s geometry. Drivers do not know the design speed for any one section and therefore will behave variably according to the speed that they consider suitable for travelling through each road element forming the section. Such speeds vary according to a large number of variables, some determined by the road and its environment and others by sociological aspects. Thus operating speed shows variation both longitudinally (changing along the road) and at each point (dispersion due to different drivers and different conditions). So operating speed should be understood not as a single value but as a distributed range of speeds.

A normal distribution is usually assumed for the distribution of spot speeds, though the properties of this distribution are variable. Figure 1 shows in a single graph the probability density functions for typical operating speed distributions for tangents and curves. As it can be seen, operating speeds usually have a higher average value and higher dispersion on tangents than on curves.

The above definition covers the concept of operating speed but it does not establish a usable value for designing purposes. Thus in practice, rather than working...
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with probability distributions, operating speed is usually taken as the 85th percentile of the distribution of speeds at which light vehicles drive in free-flow conditions with no environmental constraints. This parameter is widely used in the field of traffic engineering and road safety, for most drivers are assumed to be responsible, and thus the driver corresponding to the 85th speed percentile may be characterised as driving reasonably and prudently(III).

In the road design process there is no information available on the operating speeds that drivers will adopt, so these need to be estimated. This requires the use of empirical models, previously estimated on the basis of data observed on actual road sections. Such models should take account of geometric and/or other types of parameters. Depending on the variables selected and the types of geometric feature considered, the model will be more or less accurate.

In Spain such tools to complement geometric design are now available, allowing the operating consequences of a particular road section to be estimated through the development with models and construction rules of the corresponding operating speed profile.

As well as design and operating speeds there are other speed concepts to be kept in mind when assessing how traffic will operate. These concepts are:

- **Design speed**
  - Designated design speed, equivalent to projected design speed
  - Inferred design speed, equivalent to the Spanish specific speed

- **Limit speed**
  - Generic speed limit
  - Specific speed limit

- **Advisory speed**

- **Speed distribution**
  - 85th percentile speed. Operating speed (V85)
  - Mean speed
  - 50th percentile speed
  - 15th percentile speed
  - Standard deviation

In Spain the generic speed limit for each road is established chiefly according to the characteristics of its cross-section. But specific speed limits correspond to other factors such as the geometric characteristics of individual features, sight restrictions, roadway state, presence of slip roads, etc. The same occurs with advisory speeds. In other countries it is recommended that speed limits be established within a 5 mph range of the 85th percentile of the speed distribution of vehicles travelling at free-flow conditions(IV).

It is important to consider the correlations between design speed, operating speed and speed limits in road design(V). Certain design criteria seek to define in what events design, operating and limit speeds are in harmony with each other. Speeds are deemed to be harmonious where the designated design speed is within a specific range (e.g. ± 5 mph) of the observed operating speed, and the operating speed is within a specific range (e.g. ± 5 mph) of the speed limit. The inferred design speed should be equal to or greater than the designated design speed, while the speed limit should be less than or equal to designated design speed.

Moreover, the speeds are deemed to be inharmonious where the design speed is less than the speed limit, less than the operating speed at several points, or where both of these events apply.

The correlation between the various speed concepts shown in Figure 2a may be regarded as ideal. Figure 2b shows an interpretation of how this ideal correlation is applied in an operational design.

Where the speed limit is known during the design process, a design speed equal to or higher than this speed limit is normally (but not always) designated. But the correlation between designated design speed and speed limit varies, as the speed limit is not necessarily known during the design process and, moreover, speed limits are subject to review.
Whereas the designated design speed is determined explicitly during the design process, the inferred design speed is determined implicitly as a result of geometric design decisions. As mentioned above, designated and inferred design speeds are often different due to the fact that engineers tend to apply values for design parameters that are higher than the minimum values given by the designated design speed. The result is that many design characteristics correspond to criteria suited to a design speed much higher than the designated design speed.

Thus when a road is opened to traffic, the actual operating speeds may be greater than those expected, as shown in Figure 3a. If, moreover, the speed limit is altered to suitably reflect actual operating speeds, the correlation between design speed and speed limit is utterly changed. Figure 3b shows the resulting scenario where the speed limit is greater than the designated design speed. Such conditions are undesirable but occur frequently, jeopardising road safety, for an increase in the speed limit can only bring an even larger increase in operating speeds.

Figure 4 shows speed correlations on a road in the Valencia region. To avoid such events and to achieve harmony in speeds, it may be useful to include methods for estimating operating speeds and even to add in inferred design speeds during the design process.

4. The segmentation process

On most occasions the constraints along the route of a road are not constant but changing, especially as regards orography and adjacent urban development. From this we may deduce a need to select a changing design speed along the route, for which we must divide the road into homogenous sections. This process is known as identification of homogeneous road segments (i.e., road segmentation). Each segment will have a single design speed and will have no less than a certain length (at least 2 km is recommended). The design speed between consecutive sections should also be suitably staged.

The simplest method for segmenting a road involves dividing it according to its main intersections and cross-sectional variations. Such methods also take account of traffic density as the main variable, but omit other major aspects, such as geometry.

One of the main methods for identifying homogenous sections in view of a road’s geometry is the so-called German method[VI]. This process is based on a graphical representation of the absolute value of the accumulated deflection angles of all geometric features in the horizontal alignment. This profile is then divided into homogenous sections with approximately constant gradients, corresponding to the layout’s curvature on a similar plan. Each homogenous section is characterised by the value of its curvature change rate (CCR), defined as per equation no. 1.

$$\text{CCR} = \frac{\sum |\gamma|}{L} \quad (1)$$

Figure 3. Speed correlations (a) that can develop with low or moderate design speeds, and (b) that occur where the speed limit is increased to suit observed operating speeds.

Figure 4. Real example of speed correlations on a rural road.
Where: CCR is the curvature change rate; $\gamma$ is the angle of deflection of each geometric feature; and L is the length of the road section. This rate is normally expressed in gon/km. The minimum recommendable length of the road section is 2,000 m. Figure 5 shows an example of road segmentation.

This methodology takes account of geometric variations but not of road width or other aspects linked to road operation. Some more advanced methods which do consider such aspects are those developed by Cafiso et al.\(^\text{VII}\) or García et al.\(^\text{VIII}\).

The Highway Safety Manual\(^\text{IX}\) has also provided a methodology divided into two steps. First the road is segmented according to its main intersections, then variations in its cross-section within each segment are analysed, yielding the final homogenous sections.

5. Consistency in geometric design

One of the main features of a road's geometric design is its consistency level. The most widely accepted definition of design consistency is the conformance of a highway’s alignment and operational features with driver expectancies.\(^\text{X}\)

Driver expectancies may be of two types: a priori, i.e. the expectations that drivers have of certain types of road from their driving experience; and ad hoc, i.e. the expectations that drivers acquire as they travel along a certain road segment.

Therefore, a high consistency level means that the road largely conforms to the driver's expectations, and so will not surprise them. On the contrary, a low consistency level means that a road’s behaviour differs from those expectations, giving rise to surprises for the driver and therefore a greater risk of accidents. This is why this parameter is normally correlated to accident rate.

Most research relating to consistency and the models developed of this aspect focus chiefly on four spheres: operating speed and its variations therein, vehicle stability, alignment indices and driver workload. The most widely used criteria are based on an analysis of operating speed.\(^{XI}\) This speed is used to assess consistency either by examining its variation along the road or by comparing it with design speed. So far they are applied only on rural roads with a single roadway, which is where most fluctuations in speed occur, so it is here that there is most possibility of there being a mismatch between the speeds permitted by the layout and those at which drivers expect to drive.

The most widespread methods for assessing consistency are those developed by Lamm et al.\(^{XII}\). These provide two criteria linked to operating speed, including the difference between operating speed and design speed (criterion I) and the difference in operating speed between consecutive geometric features (criterion II). Table 1 shows a summary of consistency thresholds for criteria I and II.

Most consistency criteria offer a discrete, non-continuous result, by thresholds. The aim is to clearly indicate when measures should be taken on a road and when not. Yet reality behaves continuously. This is why other researchers suggest using continuous functions in determining the degree of consistency.\(^{XIII}\) Such is the case of studies conducted by Polus and Mattar-Habib\(^{XIV}\) and Camacho-Torregrosa et al.\(^{XV}\). In both approaches the operating speed profile of a road
section is taken as a whole, to some extent reflecting its dispersion. Dispersion in operating speeds is linked to the changes in the cognitive load of the geometric layout, so a large number of changes is associated with a higher accident rate.

A recent model developed by García et al. [49] is based on the assumption that a road’s behaviour at any one point may be estimated from the operating speed at that point, whereas driver expectancies can be estimated by the inertial operating speed. Inertical operating speed can be calculated as the moving average of operating speeds over the previous 1,000 meters. The difference between these two parameters has been called the Inertial Consistency Index (ICI). The proposed consistency thresholds are the same as in criteria I and II.

6. Application of consistency in geometric design

A safe road alignment should be easy to understand and interpret, inviting the driver to travel along it gradually to the speed levels for which each of its features were designed. This means not that drivers need know these benchmark speeds but rather that they may implicitly estimate and interiorise them.

Accordingly we need to achieve a consistent design, easily interpretable by drivers, thereby helping ensure that their expectations are not violated. Thus the aim is that drivers should perceive the road section homogenously, with no sharp changes in their level of attention.

Assessing consistency using these criteria allows us to confirm, at the road design stage, whether the road may be considered to have good, acceptable or poor consistency, and even to estimate the number of accidents that are liable to occur on it. In the event that the design of a road section is assessed as poor or acceptable, an optimisation of the design should be considered. Moreover on roads already in service, an assessment of consistency allows us to identify the more problematic areas on which redesign may be focussed.

7. Geometric design in the planning and design phases

The planning and design phases should be approached differently, for the aims sought are likewise different. While in the former the aim is to broadly define a series of possible highway solutions, with the best being opted for, in the latter the object is to attain a final design and to ascertain its impact on drivers.

In the planning phase various tentative solutions are defined from which we should determine overall characteristics, notably planning speeds, along with the sections into which the road may be segmented and the corresponding design speeds. The aim is to properly stage the various design speeds and to make the solution appropriately consistent with its environment (as regards the wider road network).

In the design phase we already have a suitably segmented road, with the corresponding design speeds. It is at this point that we should determine the geometric restrictions to be applied and then geometrically define the road.

**Limitations of the current geometric design process**

The current geometric design process has certain shortcomings arising chiefly from the way in which the

---

**Table 1. Thresholds for determining design consistency. Criteria I and II developed by Lamm et al.**

<table>
<thead>
<tr>
<th>CONSISTENCY RANGE</th>
<th>CRITERION I (km/h)</th>
<th>CRITERION II (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>$</td>
<td>V_{85} - V_j</td>
</tr>
<tr>
<td>Fair</td>
<td>$10 &lt;</td>
<td>V_{85} - V_j</td>
</tr>
<tr>
<td>Poor</td>
<td>$</td>
<td>V_{85} - V_j</td>
</tr>
</tbody>
</table>

Photograph 4. Intersections should be considered for distinguishing homogeneous road segments.
different speed concepts are considered in the design process. As described above, the fact that a road meets the criteria set by design standards or guidelines does not necessarily mean that it is safe.

The design speed imposes strict minimum values in certain design controls within a road section, such as the minimum radius or the required sight distances. Nevertheless, most geometric elements within a homogeneous road segment are not so strict, so the operating speed will tend to be higher than the design speed. This may lead to safety issues, especially those related to visibility.

Moreover, though our understanding of drivers’ operational characteristics and their relationship to safety has significantly increased in recent years, such assessments have not been included by the design process. Thus on many occasions the final road design shows major speed disparities, eventually leading to more accidents.

As to the planning phase, currently a great range of parameters are considered when analysing possible solutions, such as economy, environmental impact, capacity and operation, length, etc. Unfortunately, road safety is rarely one of these aspects. Accordingly it should be considered in more directly, if possible, through an analysis of the proposed alternatives and an estimate of their impact on the future accident rate, i.e. on substantive safety.

To date only certain countries have incorporated consistency in to their geometric design standards or guidelines, but no coherent overall process has been formulated for its integration.

Objectives

The objective of this paper is to propose a new geometric design process for rural roads. This new process integrates road safety analysis as a key intermediate step. This analysis will be made mainly on the basis of a consideration of the operational and road safety aspects discussed above. Moreover these processes will be iterative, with the aim of proposing solutions converging on a design that is consistent and therefore safe.

Proposed new safe geometric design process for rural roads

The new geometric design process for rural roads considers in operational criteria in the road design. In this design proposal account is taken of regulatory criteria, but at the same time various operational and safety aspects are assessed with a view to offering an optimised, safe solution.

Rather than detailing the tools to be used in each phase, we describe only the aim pursued. Thus the designer is given freedom in this respect. One reason for this is that the tools available evolve as know-how in the field advances.

1. General process

Basically the proposed design process seeks to include a safety assessment to the design by adjusting it to suit driver behaviour. Figure 6 shows a flow chart of the proposed design process for new-build roads.

This new design process starts with the choice of an anticipated target speed, which is the basis for the design speed. This target speed should be based on the expectations that drivers may have according to the road’s function within the highway network, orography and urban development, among other factors.

As to the planning phase, currently a great range of parameters are considered when analysing possible solutions, such as economy, environmental impact, capacity and operation, length, etc. Unfortunately, road safety is rarely one of these aspects. Accordingly it should be considered in more directly, if possible, through an analysis of the proposed alternatives and an estimate of their impact on the future accident rate, i.e. on substantive safety.

The next stage is to determine whether this design is safe or needs some changes.

In this check, the first stage is to estimate operating speed profiles (in both directions) using the corresponding models. In Spain models and construction rules are available for this purpose, such as those developed by Pérez et al.[xVII, xVIII].

The next stage is to determine the segment’s consistency value according to its operating speed profiles. It is recommended that at least the following criteria be applied:

- Models which focus on the difference between operating speed and design speed. An example would be Lamm et al.’s criterion I.
- Local models assessing the operating speed reduction between consecutive features, such as Lamm et al.’s criterion II.
- Inertial models, which may be regarded as a midpoint between the above two types. An example would be García et al.’s ICI. These will allow us to find large discrepancies between operating speeds and driver
expectancies which would not have been detected with the previous models.

- Global consistency models, which consider operating speed variability within a homogenous road segment. In this first evaluation, the road segment remains undivided, so global models are applied to the whole road.

Only in the case that all the models yield a good consistency value would the design be validated as good. Otherwise, the proposed solution should be iteratively improved. In this case the first step is to determine whether the road should be divided into homogenous segments, given the variation in external factors or the curvature of the horizontal alignment. A wide range of segmenting criteria may be used.

In the case that the road is composed by a single road segment, the designer should consider whether the lack of consistency may be due to a poor initial selection of design speed, or simply to a poor geometric design. In the former event that speed should be redefined, and in the latter the design should be improved.

Where the road consists of several segments, a design speed should be defined for each one, and then an initial geometric design should be produced for each one. It is important to remember that large shifts in design speed may not be set between consecutive sections (no more than 20 km/h).

For each section the corresponding operating speed profile should be developed and consistency assessed considering local and global criteria. If good consistency is not obtained, the designer should consider the possibility of changing the design speed and/or the geometric design.

Only once all the sections show good consistency will operating speed profiles be determined for the whole and local consistency criteria applied. In principle the road’s general consistency should be good. Otherwise, depending on what type of inconsistency is yielded, the designer should go back to the previous step and modify the relevant sections, restarting the process, and reconsidering the design speeds. Figure 6 shows an outline of this process.

In the operating phase, measurements should be taken of operating speed and available sight distances, allowing us to define a profile for each of these variables along the road. On the basis of the road’s actual operating speed profiles and the available sight distance profiles, speed limits should be established. Thus we will achieve the harmony of speeds referred to in our introductory section, resulting in a safer road design than that currently obtained from a mere geometric check of the layout according to applicable standards.
2. Adaptation to the planning stage

Adapting the proposed methodology to the planning phase chiefly involves identifying which of the possible alternatives envisaged are safest in terms of consistency. As no detailed design is to be produced, the flowchart is appreciably simpler than in the case of a new-build design.

The first step of this phase is to start developing a set of various alternatives, not yet highly defined, considering the new road’s intended functionality. A pre-design will be made for each one, with a first attempt at setting a design speed. On this basis the consistency of each solution will be assessed, using only global criteria. The alternatives with a good degree of consistency may be defined as definitive, while those with poor consistency should be segmented, following the process established for each differentiated section.

With an analysis of global consistency, accidents with victims can be estimated for each alternative. Thus we have a more direct knowledge of the safety repercussions of each alternative. This criterion therefore becomes an objective measurement (substantive safety) that may also be considered in the process of choosing the final alternative, along with the other criteria considered to date.

Application to safety assessment of roads in service

Roads currently in service would have been designed by the traditional geometric design process. Consequently parameters such as gradient transitions and sight distances are dependent on the design speed, which on many occasions is far from the operating speed. Moreover, on older roads no account might have been taken of maximum proportions between the radii of consecutive bends.

Besides, a road is often designed as a single entity, with no clear division into segments with different design speeds. This may generate adaptation and a lack of consistency which generally lead to higher accident rates.

Our proposed methodological innovation may be used to determine to what extent such issues may affect the safety performance of an existing road. Thus it is possible to determine whether it has potential safety issues, and, if applicable, to identify these issues in order to fix them.

A safety assessment of an existing road will be essentially based on an analysis of its consistency, both global and local. Firstly its geometry should be plotted. On this basis the operating speed profiles will be determined and used for an analysis of consistency and segmentation.

Consistency analysis taking account of design speed (criterion I) may detect whether the vehicle operations on a road are ill-suited to its minimum features or its environment. Criteria such as criterion II (Lamm et al., 1999) or the inertial criterion (García et al., 2013) would identify any design faults, while a global consistency analysis for each section would determine the consistency between them, and allow us estimate up to a point the accident rate.

1. Adaptation to the redesigning of roads

The methodology presented here may be adapted to the redesigning of roads, albeit with slight variations. The redesigning of a road is generally prompted by the observation of a number of traffic accidents higher than that which is to be expected, which in principle suggests an involvement of the infrastructure factor.

The first major difference is that we do not set out from a design speed but rather infer one from the road’s geometry. So the first step is to determine the geometric characteristics of the road to be redesigned (Figure 7). These characteristics may be ascertained either from the relevant project design or by geometric plotting. On this basis we determine the most restrictive geometric controls and the inferred design speed.

The next step is to determine whether the road, in these conditions, has appropriate consistency, for which the process is similar to that for a new design. First we will estimate the operating speed profiles for each direction, and then we determine consistency, which will presumably yield a poor value. The road will then be segmented. If it consists of only one segment, we will first reconsider its design speed (i.e., designated design speed), then redesign the road until appropriate consistency values are achieved.

If the road consists of several sections, a similar procedure will be followed for each one. Thus we will first identify the limiting geometric controls so as to infer the design speed. We will examine the consistency of each segment so as to determine whether the inferred design speed is suitable or is liable to be reconsidered. As soon as all the segments yield acceptable consistency values, we may proceed to the next step (combined analysis), in which local criteria...
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Geometric design is the most important phase in the definition of a road, since it establishes the final road alignment. This final result must meet the key goals while satisfying the existing constraints.

As mentioned above, design speed should be based on the road type and the external constraints (orography, existing developments, etc.). This variable should be determined by the designer, to which end it is recommendable to draw up tables to assist the process. It is recommendable for these tables to be a guide, giving the designer freedom to take the final decision.

The choice of operating speed model is also left open. There is a large number of models with multiple differences, though generally speaking they are highly variable in geographic terms, so we recommend the use of local models where available. In the case of Spain, calibrated models and construction rules are now available.

As to consistency models, global ones have the advantage that they allow us to estimate the number of accidents, though without focusing on the most hazardous spots. In any case they should be applied on homogenous segments, otherwise the results might be biased.

As to the redesigning of existing roads with high accident rates, the aim is to convert the current geometry into a safe geometric design with minimal changes, and so there is less flexibility than with new-build roads. This is why on occasion, when setting out from roads with poor initial consistency, it may be practically impossible to produce a design with good consistency at a reasonable cost (as good consistency would require a dramatic change of the alignment). So in these cases designs with fair consistency are allowable.

Both the traditional design process and the one proposed here end with the setting of speed limits. These are established according to the available sight distances and the operating speed, both of which parameters are measured once the road has been built. With operating speed models we can estimate these profiles with a certain degree of reliability, so we are more likely to achieve harmonious speeds than with a traditional design. In the latter the operating speeds may be considerably higher than the speed limits set (conditioned by the available sight distance) and the designated design speed with which the necessary sight distance was calculated at each point.

In the planning phase, when selecting alternatives this methodology allows us not only to identify which designs are valid from a road-safety perspective but also, using consistency models, to estimate the number of
one in particular given that they are variable according to geographic region and in their apprehension of the correlation between accident rate and geometric design. Three types of instrument are mentioned: operating speed models, segmentation and consistency models.

Finally we have extended the flow chart for new design, the planning phase and the redesigning of existing roads. Though the working process is similar in each case, there are small variations. We also indicate how this procedure may be used to assess the degree of safety on existing roads, thereby better identifying in what events a road should be redesigned and where to focus such efforts.

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The article raises the question of the importance of road maintenance, especially in times of recession. Maintenance funds tend to shrink due to budgetary constraints, but the author makes the point that maintenance is not only a question of the available funds. Other equally or even more important factors are also required: an explicit maintenance policy, an adequate structure in the public authorities responsible for the road networks, material resources and above all competent and experienced human resources and technology adapted to specific needs. With respect to the last point, the author underlines the importance of preventive maintenance techniques.

**Key words:** Road, Maintenance, Economics, Investment, Prevention.

**Introduction: Prevention is better than cure**

The 2007 financial crisis in the United States led to a global recession that has hardly hit the Southern countries of the European Union (EU) - Greece, Cyprus, Italy, Spain and Portugal, all belonging to the Eurozone (the European common currency area). In these countries the global financial crisis coincided with local crises originating in serious structural problems inherent in the economies themselves, especially in the banking and real estate sectors and to imbalances within the Eurozone (due, among other reasons, to the absence of a common fiscal policy). These countries have also suffered runaway growth of the public debt both in absolute terms and as a percentage of the gross domestic product: 169% in Greece, 89% in Cyprus, 128% in Italy, 88% in Spain and 122% in Portugal.

This increase in public debt is the result of ongoing imbalances in fiscal and budgetary policies and assumption by the state, albeit indirectly, of a significant proportion of private debt. The need to guarantee collection of the debt by creditors was used by the International Monetary Fund (IMF), the European Central Bank (ECB) and the European Commission as a pretext to impose harsh economic and budgetary adjustment policies. For the time being these policies have only managed to impoverish broad sectors of the population, provoke a dramatic increase in unemployment, especially of young people, and virtually freeze bank credit to companies and individuals. The troika has also imposed dismantling of the public services, especially in Greece and Portugal. Thus the Southern EU countries are immersed in a deep recession with no end in sight made worse by unstable governments, a situation that only Spain has managed to avoid until now.

This is the background of a drastic decline in public investment and therefore in funding for transport infrastructures. These investments, especially in Spain and Portugal, had played a vital role in both modernising the infrastructures and driving the economy in recent decades. They had also been a key factor in enhancing competitiveness. Now however, the option of continuing with these investments as a buffer against recession, as has occurred in other countries in other times, has been relinquished.

But the decline in public investment has not affected all modes of transport to the same degree. In particular, in Spain it has been far more detrimental to road transport...
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than to other modes: the process of development and modernisation of the road network has ground to a halt. Fortunately, the ongoing momentum of this development from the mid-80s has meant that currently, in spite of everything, accessibility to practically all the national territory is ensured and the only mobility issues are confined to a few big cities.

However, the indispensable work of refurbishing and improving the existing roads has been gravely affected by plummeting investment. In some of them the effects of lack of maintenance is already becoming evident, especially in the superstructure: pavement, signalling and vehicle restraint systems. It seems as if the public authorities who own the roads are insufficiently aware of the importance of road maintenance precisely in these times of recession. Therefore, if the question “what is required to carry out satisfactory road maintenance?” was asked today in Spain as in other countries the first response, the most immediate, would be money. Keeping all the above in mind the answer seems logical. However, the correct answer is not that easy. Money is necessary, true, but not only money. Many examples could be given of how things may fail to turn out better with more money. In the final analysis, provided that certain minimums that should not pose a problem in Spain are exceeded, the available budget is no more than kick-off data.

**THE NEED FOR A MAINTENANCE POLICY**

The first requirement for road maintenance, and even more in times of recession, is a maintenance policy or, to put it another way, the political will to devote attention, effort and resources to road maintenance. This means preserving the roadway heritage and acting on the associated infrastructures to address the needs of the citizens, many of which cannot be met by other modes of transport. Policy makers must be aware that roads in fair condition are essential for efficient freight transport, to satisfy the need for the movement of people in safe and reasonably comfortable conditions at all times and to ensure the accessibility of the entire national territory. All the above must be kept in mind without forgetting that pavement in poor condition entails an increase in both fuel consumption and emission of greenhouse gases.

It seems that in times of economic downturn the need to make financial adjustments leaves environmental concerns in second place. This is totally unjustified. Sustainability of the road network is a vital requirement for economic recovery and in this sense environmental criteria must be taken into account. Therefore, the objectives of the road maintenance policy must include enhancing road transport efficiency from the energy-related and environmental points of view.

**MAINTENANCE STRUCTURES**

The second requirement for road maintenance is the existence of a specific organisation in the competent public authority. It is vital for this structure to be independent of other roadway engineering activities such as design or construction since otherwise the latter end up taking priority over the maintenance aspects. It is also advisable that the maintenance structure is separated from that devoted to operation in the strict sense while maintaining the unity of the general objectives, since operation in all its aspects is generally more absorbing and maintenance suffers as a consequence. These considerations are applicable regardless of whether the aforesaid structures are managed by a public authority under the traditional model or by a public or public-private agency with a greater or lesser degree of functional and financial autonomy.

**HUMAN AND MATERIAL RESOURCES**

The third requirement for performance of satisfactory road maintenance is the availability of suitable human and material resources both in the specific organisation, to which reference has been made above, and in the companies awarded contracts under a variety of formulas (direct contracts or public-private concessions) for implementation of the maintenance tasks or part of it. Both the human and material resources should be devoted permanently and exclusively to maintenance.

With respect to the material resources it is necessary to have machinery, building materials, stockpiling areas and workshops, operational control centres, etc., available. While not as demanding as road operation activities in the strict sense, maintenance also requires coordination based on an adequate communications system. Moreover, road maintenance requires specifically assigned personnel with the widest possible experience in the field, highly specialised in all the tasks involved and adequately trained to work at all levels of responsibility: engineers, technicians, skilled operators, etc.

Along these lines, it must be emphasised that recruitment of personnel to address road maintenance cannot be the result of improvisation. As a general rule the technical competence and experience required are greater than those demanded by other kinds of task such as construction.
**Financial and Economic Resources**

Evidently, in conjunction with the above road maintenance requires financial and economic resources. The following three features are indispensable prerequisites for funds devoted to road maintenance:

- **Stability**, without significant increases or decreases from one year to another (unless required to address new roadway developments or to absorb cost increases due to inflation).

- **Advance knowledge** by all the agents involved to ensure that maintenance tasks are properly planned and that the companies concerned in the processes can adapt their structures to meet the expected performance levels.

- **Guarantees** for long periods of time since road maintenance planning must be done with a long or medium-term perspective. This logically entails the need for a guarantee concerning the origin of the funds which, if they proceed exclusively from government budgets, must be assigned for multi-annual periods.

It is perfectly well known that the scarcity of the available funds is less serious than the lack of long or medium-term guarantees as to their actual availability, since the latter precludes planning of activities, especially of those involved in maintenance. Unfortunately, in times of recession or budgetary cuts the majority of the public authorities paradoxically tend to devote the limited funds available to construction of new roads instead of maintenance of those already in service. If the cuts entail constraints on investment in roadway-related areas it would be understandable if new developments were put on hold, but not that maintenance of existing infrastructures is neglected.

For several decades now there has been consensus on the minimum annual investment required to maintain a typical road network in an acceptable condition. This minimum is reliably estimated at 2% of the net value of the network in question. This can increase to around 3% if activities more closely related to operation are also taken into account. Experience in Spain has shown that 50% of these amounts is required to maintain the pavement in particular in an acceptable condition, i.e. between 1 and 1.5% per year of the total net value. The total net value can be calculated by various methods which all give different results, but this variation is irrelevant in practice.

Together with traditional budget-based funding, where the resources originate in annual or multi-annual allocations by the competent legislative body (parliament), extra-budgetary funding has been of increasing importance in many countries over the last two decades. This finance may be public, private or mixed and usually takes the form of a fund managed by a government agency with the autonomy (which does not imply lack of control) to use a variety of resources.

It has not yet been demonstrated that any particular model is more efficient than others, and examples can be found to support or refute all of them. The choice of model must be based on achievement of the objectives outlined in the maintenance policy with the lowest cost to the taxpayer. These costs must of course include not only the actual measures but also the cost of the bank loans and the earnings of private capital investments, the environmental costs and those passed on to the end user as a result of the maintenance tasks themselves or of the condition of the pavement. Unfortunately, the choice of model is too often conditioned by both ideological prejudices and by the influence of various lobbies. Given this scenario it is no wonder that there is no guarantee as to their real efficiency.

**Availability of a Specific Technology for Maintenance**

The last prerequisite to enable satisfactory road maintenance is the availability of a specific technology. In this respect it would be as well to emphasise that road maintenance technology is actually more complex than that required for design or construction. And as commented above, wider experience is required both to develop and to apply it.

For technical and financial reasons, the competent public authority or agency must have implemented a valid management system properly adapted to the specific features of the network in question (I). In addition there must be a wide range of road monitoring equipment and methods available, especially to assess slip resistance and surface roughness. Ensuring that pavement rehabilitation procedures are suitable for addressing the condition of the road network and free from unnecessary rigidity in their approach to the design of structural or surface rehabilitation is also of great importance. It would be fitting to end by highlighting the importance of refining preventive maintenance procedures which are in the end far more efficient than corrective measures. We shall return to this point later.

A problem may occur at the outset in the use of management systems due to the lack of a clear distinction...
between service indices and condition indices. The former term refers to strictly operational criteria, i.e. to the service provided, while the latter refers to the elements of the road that will be the object of maintenance tasks. The problems deriving from the use of an excessive number of indices are even more serious. Efficient management can and must be based on a limited number of indices, perhaps as few as four or five. Basing management on numerous indices does not enhance it, but can make it extremely complicated, even more so if the experience in handling them is lacking.

I must point out a relatively common conceptual error in relation to this aspect: in many cases management is not based on indices as such but on certain parameters deriving from measurements. It should be kept in mind that an index is simply a score or rating with which to objectively assess the service provided (service index) or the condition of an infrastructure that supports said service (condition index) in a quantitative manner and at a certain point in time. The quantification and objectification are performed by measuring one or more parameters in each case. These parameters represent the data to be used by the relevant transfer function to determine the value of the index. If any of the “indices” to be used is the result of a subjective judgement, then it must be rejected as an index.

An index provides an evaluation at a particular point in time. Both to act as a management tool and to properly establish the reference thresholds (of initial quality, attention or advisable measures, required measures and unacceptability) it is essential to know how the index can vary over time, i.e. it is imperative to have performance models. And to have performance models, a priori estimates must always be carried out in the first place. This means that it is necessary to begin by proposing models referenced to the technical literature or to develop them using suitable mathematical techniques (Markov analyses, for example). These models will have to be calibrated and adjusted over time as real measurements of the parameter or parameters on which the index is based become available.

Performance models are one of the components of a management system. Thus it is sufficiently clear that if a management system has not been implemented it is more than doubtful that any performance models used will be properly calibrated. Consequently, using index thresholds that must be described as arbitrary makes very little sense.

And if a management system is absent then the various maintenance-related strategic options - some basically preventive and others predominantly corrective - cannot be properly established and even less adequately assessed. To sum up, if a management system is not implemented the decisions will be made on insufficient grounds, and although it is indisputable that in the final analysis they will be made by the policy makers, said decisions will be at the mercy of political criteria, too often conditioned by political clientelism, short-term electoral interests or the pressure of the mass media.

**The Importance of Preventive Measures**

In the context of maintenance management, each possible combination of measures (both routine maintenance and rehabilitation) performance of which is feasible over time in order to comply with the objectives set by the relevant maintenance policy constitute the maintenance strategy. It is easy to understand that any maintenance programme implicitly includes a certain strategy. Each strategic option will have a certain cost and will produce a certain effect on the roadway and on its foreseeable development from the moment each measure is implemented. For this reason, among other things the management systems must be capable of performing a comparative analysis (technical and financial) of the various strategies open to consideration, provided that they are all aimed to a similar extent at achieving the objectives of the maintenance policy. At all events it will be necessary to assess the degree of achievement of these objectives for each possible strategy.

Any possible maintenance strategy necessarily falls between two extremes:

- A strategy based mainly on prevention, consisting of measures with a limited cost and relatively frequent over time. In this model the condition indices fall relatively slowly (in no case are the relevant advisable measure thresholds exceeded). As is well known, the curves of the relevant performance models are saw-toothed (Fig. 1).

- The basically corrective strategy on the other hand consists of more costly measures less frequent over time. Therefore the condition indices can fall significantly, even reaching levels below the unacceptability threshold. The curves of the relevant performance models are then a succession of complete curves (Fig. 2).

In practice the aforesaid extreme approaches are represented respectively by the following options for road pavements:
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Application every few years (usually between 3 and 6 depending on the intensity of heavy traffic and weather conditions) of a surface renovation (depending on the type of road: chip seal, slurry seal, SMA, or asphalt concrete with a thickness of 3 to 5 cm) combined with a permanent sealing of cracks and immediate repair of other localised damage that may arise.

Structural rehabilitation every several years (usually between 12 and 16, depending on the intensity of heavy traffic and weather conditions) by overlaying, milling and replacement (more overlay) or recycling (more overlay) combined with the repair of only major localised damage that may arise (large depressions, major potholes, etc.).

Public authorities and agencies that have not put a valid management system in place tend to apply maintenance strategies that actually fail to implement any planning at all and are usually closer to the second extreme cited above. Thus there is apparently a saving in maintenance costs (although a comprehensive financial analysis would show that this is not so in the majority of cases), but significant costs are passed on to the user to the extent that poor pavement conditions entail notably superior operating costs and downgrading of the traffic safety conditions (in fact it is a kind of shadow tax with clearly negative effects on the efficiency of the system).

Conclusions

The drastic descent of transport infrastructure-related investment has occurred in the context of the current recession. This decline is provoking a situation where indispensable rehabilitation and improvement roadwork are paid less attention than they deserve.

Recruitment of personnel to address road maintenance cannot be left to improvisation. As a general rule, the technical competence and experience required are greater than those demanded by other kinds of task such as construction.

The following features are an indispensable prerequisite for funds devoted to road maintenance: stability, without significant increases or decreases from year to year; advance knowledge by all the agents involved; long-term guarantees of availability.

The choice of model must be based on achieving the objectives outlined in the maintenance policy with the lowest cost to the taxpayer. These costs must logically include, not only the actual measures, but also the cost of the bank loans and the earnings of private capital invested, the environmental costs, and those passed on to the end user as a result of the maintenance tasks themselves or of the condition of the pavement.

For technical and financial reasons the competent public authority or agency must have implemented a valid management system properly adapted to the specific features of the network in question.

I would underline the importance of refining preventive maintenance procedures which in the end are far more efficient than corrective measures.

Public authorities and agencies that have not put a valid management system in place tend to apply maintenance strategies that are usually closer to the purely preventive approach. This brings an apparent maintenance cost saving, but in fact the costs are passed on to the user.

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Development of bridges in Spain

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ABSTRACT

The project engineering and construction of bridges in Spain over the last two decades has drawn international recognition of the Spanish construction industry. The first half of the 20th century was especially rich in the creation of beautiful, economical structures. Later progress has enabled optimisation of classical formats (girder bridges, slab bridges, incrementally launched bridges, bridges of concrete or steel, arch bridges, cable-stayed bridges...) at the same time seeking new formal horizons and construction methods.

The article describes a series of bridges built in Spain during the last twenty years, selected from among the significant contribution of Spanish engineers to the development of this aspect of the construction industry. They are ordered by type: girder bridges, arch bridges and cable-stayed bridges. Specifically, the article considers bridge over the River Duero in Zamora, the Zizur, Tina-Minor, Garcia Sola, and Gorostiza bridges, the Endarlatsa bridge, the Galindo River bridge, the bridge over the Ebro river in Logroño, the footbridge over the river Ebro at the Zaragoza Expo, the Príncipe de Viana bridge over the river Segre in Lleida and the bridge over the Bay of Cadiz.

Key words: Bridge, Singular projects, Construction, Engineering, Project engineering

INTRODUCTION

It could be said that progress in bridge construction in Spain has become a worldwide benchmark. Years of constant construction and numerous engineers thinking of what has been done and how to improve it have fostered an excellent construction industry that currently operates on five continents. It is precise, lean, accurate... It is economical and fast.

Bridge is just one of the words written in the book of roads, but it is here that we will focus our attention.

The progress of steel, concrete and mixed material bridges in the 20th century was spectacular. The accuracy of current methods of calculating loads and deformations endows engineers with great confidence when adopting new configurations. This is only possible given the high degree of control over the variables that constitute the sphere of contemporary construction.

The first half of the 20th century was especially rich in the creation of beautiful, economical structures. It was so good that it almost detained the progress of design, tied as it was to a series of very efficient classical solutions. Construction and construction processes associated with classical archetypes made typological progress extremely difficult due to the fear of entering potential quicksands beyond the safety of the classical terrain.

Progress in Spain has been good, I would even say excellent: the classics have been improved (girder bridges, slab bridges, incrementally launched bridges, bridges of concrete or steel, arch bridges, cable-stayed bridges...) and engineers have sought new formal horizons and construction methods.
The following is a selection of Spanish bridges from the last two decades chosen from the vast contribution of Spanish engineers to bridge development and divided into three groups of recent bridges according to type: girder bridges, arch bridges and cable-stayed bridges.

**Duero River Bridge, Zamora (2010)**

The distance between both carriageways was so great at the point where the Ruta de la Plata motorway crosses the Duero (Figure 1) that the idea of building one pier with four arms (Figure 2) was abandoned in favour of two bridges, each with its own pier. The separation of the axes of the two carriageways is 20.5 metres and the longitudinal arrangement is six spans of 34.5 m + 36 m + 49.5 m + 72.00 m + 49.5 m + 34.5 m.

The V-shaped pier is 7.9 m high with a longitudinal dimension of 40.9 m.

Longitudinally, the bridge consists of a 90.5 m-long box girder resting on a U beam with a depth of 1.9 m and width of 3.1 m. Prefabricated slabs with 3.5 m of overhang on each side are placed on the U-beams. All the components - the V-shaped piers, box girder and deck slabs - were prefabricated (Figure 3).

**Zizur Bridge, Navarra (2002)**

This construction solves a problem posed by the exit from Pamplona of the new highway to Logroño. The bridge was constructed for the Government of Navarra at a point where the highway bisects the residential town of Zizur Mayor, dividing it into two (Figure 4).

The Zizur project had three main objectives. One was simply structural, related to the criteria for building a bridge on a circular roundabout. The second, equally important, was to enable a pedestrian link while reducing the visual impact produced when passing from one side of the park to the other and crossing a multi-lane highway (the park itself had to cross the highway). And the third objective, imposed by the Government of Navarra, was to create a landmark, a gateway on entry to or exit from Pamplona for travellers arriving in or leaving Logroño.

Like a circular roundabout, then, a 360° disc was build supported at only four points to solve both the traffic problem and the structural criteria at the same time.
Constructing a “plate” with a 47.2 m inner diameter, a hole in the middle and an outer diameter of 73.8 m as a structure resting on only four points posed challenging analysis of structures problems. The resulting torsion and the associated deflections are formidable, which means that pre-tensioning was a complex task. However, the final formal impression is striking and surprisingly pleasing to the eye. The cross section of this plate or disc is also circular and its edges have been treated with great care (Figure 5).

A separate structure coupled to the road bridge and surrounded by gardens, to favour the aforesaid reduction of visual impact, was used for the pedestrian bridge.

Finally, in accordance with project management, the idea was to construct the gateway to and from Pamplona. This followed the success of the Ventas arch, but in this case with two arches with spans of 100 m each instead of only one.

**Tina Menor bridge**  
**Cantabrian highway, Cantabria (2001)**

This is a continuous, 378.5 m long bridge formed by four spans of 64.25 m + 125 m + 125 m + 64.25 m.

The three reinforced concrete piers are 18 m, 33 m and 37 m high respectively (Figure 6).

The transom of mixed construction is 30 m wide with a constant depth of 6.5 m. The cross-section consists of a central 10 m-wide box with a 10 m of lateral overhang each side. The lateral overhangs are supported by a triangular truss that constitutes two new lateral cells that help the central box to handle torsion. The non-linear behaviour of this bridge and the long-term interaction of the concrete slab and the steel girder were subjected to exhaustive analysis. The concrete slab is pretensioned (Figure 7).

**García Sola bridge, Badajoz (2004)**

Highway N-430 crosses the Guadiana River at the foot of the García Sola dam. The road crosses the river at a height of fifty metres at a point where the dammed river is a hundred and twenty metres wide. The carriageway is twelve metres wide and consists of two lanes. The bridge was required to cross an irrigation canal, the river and an access road to the dam.
The solution is a continuous tubular lattice structure of constant depth composed of five spans. The spans are 99 m, 132 m, 132 m, 110 m and 88 m for a total length of 561 m and width of 14 m (Figure 8).

The spatial lattice has a triangular cross-section. The lower chord is a single one-metre diameter steel tube while the upper chord is formed by two eighty-centimetre diameter tubes joined to the reinforced concrete upper slab with which it forms the mixed steel and concrete section forming the deck. The depth of the lattice girder is seven metres between tube axes.

The lower chord support is achieved by bifurcation of the lower tube on approach to the piers and abutments to enable the seating devices to be placed five metres apart. This assures the stability of the curved bridge.

The diagonal members of the lattice are steel tubes with a diameter of 50 centimetres arranged spatially with a separation of eleven metres. With this arrangement four tubes are joined to the lower chord and two to each of the upper tubes. The diagonals are welded directly onto the main tubes without using gusset plates, which contributes to the orderly, uncluttered aspect of the structure.

The upper tubes are joined every eleven metres by a steel double T-beam to assimilate the horizontal transverse load transmitted by the diagonal tube component (Figure 9).

Lattice beams are more easily deformed than web plate girders. To counteract this tendency two pretensioning cables were placed which extend from the lower chord in the centre of the span to the upper tubes on the piers. This method appeared more economical than increasing the thickness of the diagonal members at the support points.

The deck slab is twenty-five centimetre thick reinforced concrete on a truss of double-T girders to reduce the gap of fourteen by eleven meters formed by the upper grid.

The piers are made of reinforced concrete with a constant cross-section elliptical columns and a support head that widens to receive the lattice seating device. The piers are between twenty and forty metres high. The column is a hollow core structure three metres sixty centimetres across the major axis and two metres forty across.
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the minor axis of the ellipse. The column walls are forty centimetres thick. The foundations are reinforced concrete footings, since the rock is close to the surface, except on the river banks, where it was necessary to excavate nearly four metres.

**Gorostiza Bridge, Bilbao (2007)**

The southern access to metropolitan Bilbao crosses the Gorostiza reservoir at a narrow point with twin tunnels on the northern or city side. To the south the two carriageways come together in order to reduce the impact on the hillside. The bridges, one per carriageway, are located in an area of great scenic beauty (Figure 10).

This is the bridge one has always wanted to build. It leaps effortlessly from one hillside to the other without intermediate support.

These two virtually identical bridges have a central span of one hundred and thirty metres and two balancing spans of thirty metres each. Embedded in the abutments, these end spans are enclosed in a housing that allows them to dilate freely and acting as the counterweight of the central span. Each deck accommodates three lanes, two hard shoulders and lateral barriers in a total width of thirteen metres and sixty centimetres.

The central span is formed by a box composite girder with variable depth from one metre ninety centimetres at the centre span to five metres thirty at the intersection with the counterweights. The box girder has inclined web plates, which leads to a bottom plate is of variable thickness: from two and a half metres at the abutments to five metres at the centre. It is transversely stiffened every four metres by inclined props and frames.

The concrete upper slab is thirty-five centimetres thick with three-metre lateral overhangs where thickness is reduced to twenty-five centimetres at the edge. There is also a concrete lower slab to create a double mixed effect with a variable thickness ranging from forty to eighty centimetres that runs twenty metres from the support towards the centre of the span (Figure 11).

**Duero River Bridge, Zamora (2012)**

This is not a multiple arch or a series of arches but a continuous bridge 424.5 m long with six spans with 92 m between support points.

The cross section is a box girder of variable depth between 9 m over support and 2 m at the crown. Total width is 14.7 m and webs separation is 8 m (Figure 12).

The depth of the bridge itself reaches the foundation a sliding bearings ensures that horizontal loads are not...
transmitted to the substrate. The effect of a multiple arch bridge is an interpretation of the neighbouring traditional multi-arch bridge using contemporary materials and engineering.

Abutment 2 is special. It had to be placed under a circular roundabout which distributes traffic to roads on the riverbank. The roundabout was elevated to avoid the enormous circular wall that it would otherwise entail. It also had to allow for the route of an extremely scenic riverbank path (Figure 13).

**Viadotto Corso Argentina, Eastern Padua (2003)**

This bridge is an example of the many Spanish design and engineering projects in other countries.

A 543 m long viaduct consisting of 11 spans of 40 m. + 9 m. x 51.5 m. + 40 m, it was designed for the Padua ring road at the intersection with the Venice highway.

The viaduct has to cater for a plethora of ramps and interconnections that link it to the Corso Argentina and the Venice highway (Figure 14).

The central body is 32 metres wide and is composed of two trapezoidal steel boxes 2 m deep, 2.7 m wide at the base and 15.5 m at the top with two intermediate vertical webs with a separation of 6.3 m (Figure 15).

Two special problems had to be solved: the deck support and the very complex problem of how to integrate the structure of the interchanges that ascend and descend between the bridge and the main highway.

The first was solved by using V-shaped pier 10 metres wide at the base and 20 at the head. The inclination of the piers produces a substantial horizontal load absorbed at deep level with a prestressed transverse frame.

Having a single pier, although it is bigger than two individual piers, is considered to be important to support the double transom that forms the deck (Figure 16).
The 1.4 m-wide steel piers are embedded in the transverse frame and in the slurry wall foundations. This longitudinal constraint was necessary due to the conditions extremely flexible and poor substrate.

The second problem, the support of the access ramps and with a visually pleasing connection to the main body was solved by differentiating ramps clearly separated from the main body (ramps 3 and 4) and ramp 2, which ascends almost parallel to the viaduct. In this case the ramp is suspended from the viaduct trough special transverse cantilever beams. They were initially suspended from brackets but excessive torsional deformation made it advisable to embed the support in the main girder (Figure 17).

Three arcs with a span of 150 m each were installed on the median axis for lighting and embellishment.

**Endarlatsa bridge, Navarra (2007)**

The new Endarlatsa Bridge crosses the Bidasoa River at the triple boundary junction between the northern Spanish provinces of Navarra and Guipúzcoa and France. The new bridge is part of general improvement of the N-121-A highway that connects Irún and Pamplona. It is located upstream from a previous 37 m span reinforced concrete arch bridge inadequate to handle the current traffic.

A fundamental constraint of the new bridge design was its protected location: the environmental impact study required the least possible contact with the river, both during erection and once concluded.

The bridge is 190 m long comprising ten spans of 15.00 m + 8x20 m + 15.00 m. The five 20 m centre spans rest on a parabolic arch spanning 100 m, with a 10 m rise at the centre.

The river crosses the river in a marked skewed angle and as regards to horizontal alignment the greater part of its length is developed in a long-radius (3500 m) that is linked with a tighter radius (320 m) by means of a 66 m long clothoid. The surface is adjusted transversally to the above alignment by ensuring adequate camber variable between 2% and 7%. The vertical alignment of most of the layout has a constant slope of 2.5%.

The deck width is variable as the roadway progressively widens going from 11.85 m to 15.65 m. It is formed with a composite steel-concrete box-section. The steel box girder has a constant width of 5.0 m, with 0.8 m deep webs and 0.50 m top flanges. Side cantilevers are supported by steel ribs spaced at 2.5 m. Their length...
is adjusted to accommodate the variable width of the road platform. Concrete partial precast slabs are placed on top of the steel section and a 0.2 m thick reinforced concrete a cast-in-place slab was poured over them. The concrete slab is connected to the steel by means of studs located on the top flanges and on the transverse ribs. (Figure 18)

The deck is continuous along the full length and is supported by steel piers. Over the river crossing six piers rest on the 100 m steel arch. Deck is supported over piers by single hinged and sliding bearings (elastomeric in one pier and pot bearings in all remaining), except at abutments and at the two piers placed over the arch springs:

- At the abutments, transverse rotations and transverse reactions are blocked. The firsts placing a double set of bearings connected to the box section by a transverse diaphragm. The second with a steel blocking in the axis of the box section. One of the abutments is also used to fix the deck in longitudinal direction with a steel hinge.

- Piers at the spring of the arch are rigidly connected to the deck. All the others piers placed over the arch have pot bearings, hence, only vertical reactions are transmitted to the arch.

This arrangement was chosen after a comparative analysis between the deck and the arch strength requirements. Regarding the arch requirements it was found that it was advantageous to liberate the arch from other than vertical reactions rather than connecting deck and arch to resist eccentric and horizontal loads. In that configuration the deck had to resist all eccentric loads and wind loads in the 100 m length between the piers over springs. The slender composite-steel box section was not enough to resist the resultant torsional moments –transversal deformations due torsional rotation were not admissible- For that reason the deck torsional stiffness above the arch was increased: the two top flanges of the box section were replaced with a full top plate, thereby obtaining a fully steel box section.

The arch vertical geometry is quite slender, only 10 m rise for a 100 m span. Its horizontal alignment matches that of the road; this implies a spatial configuration of its geometry. This horizontal curvature, combined with the parabolic curvature in elevation, results in a warped curve.

The arch section is made of a pair of streamlined steel tubes 1.00 m in diameter and 25 mm thick, filled with high-strength low shrinkage grout without auxiliary connectors. Therefore the behaviour of the arch is also that of a composite steel-concrete section. The arch section is completed by joining the two tubes at the upper and lower sides with two 25 mm thick horizontal tangent plates, stiffened longitudinally and transversally. (Figure 19)

The transverse sectional forces due to the curved geometry created additional sectional forces on it. As mentioned before, due to the limited horizontal curvature of the deck these forces were not excessive large and by simply adjusting the transverse dimensions of the arch section it was possible to achieve the required levels of transverse stiffness and strength. The width of the transverse arch section varies between 3.00 m at the key and 5.00 m at springs. This arrangement results in a strong section with appropriate vertical and transverse stiffness, the latter being definitely greater at the springing line where the stresses are maximal. The
instability problems to which such slender configurations are usually susceptible (increased by the spatial arch configuration) are then fully under control.

The resultant geometry was quite complex, each side tube geometry is different arising from the combination of the horizontal curve of their axis and the aforementioned variable width. This geometry was intensively controlled during construction and trial-and-assembly was prepared in the steel workshops.

The abutments are standard reinforced concrete works, located away from the water course.

Foundations were laid directly on granitic rock outcrops in the area. On the Navarra riverside during construction it was detected a fill layer greater than expected. Direct foundation was changed to deep foundations with 1250 kN steel micro-piles. The micro-piles are bored into rock and alluvium using the “tube-à-manchette” grouting technique, with special precautions to avoid any grout leak into the river.

The most singular aspect of the construction process was the method for erecting the arch by tilting its semi-arches. This was necessary to comply with the environmental requirement of no impact on the river.

The sequence of operations was as follows:

- Vertical erection of the two complete semi-arches over provisional hinges.
- Rotation of the semi-arches until they lean against one another; this operation is controlled by means of tie elements.
- Alignment, provisional blocking and welding of the semi-arches at the crown. Bloking of the provisional spring hinges.
- Placement of the piers over the arch.
- Erection of the steel deck, by sections.

An auxiliary structure served as vertical support for each semi-arch at the erection and welding stages. It was also used as reaction element in initial stages of lowering operation for the long-stroke jacks used the break the equilibrium.

If rectification of the arch closing position were necessary it would have been done by means of another of hydraulic
After the arch tilting provisional hinges were blocked longitudinally and then arch spring were concreted. The retaining devices used to control the lowering operation were installed on both abutments. These devices comprised two 2000 kN hydraulic units that rotated jointly, with the support of a long-stroke jack. The semi-arch was joined to the anchor of the pulling unit by means of a locking pin.

The horizontal curved geometry of the arch made the tilting operation more delicate as it is not possible to align the retaining cables with a curved axis. Transverse reactions were then also transmitted to the semi-arches. Accurate previous analysis and delicate verifications during the operation were made to control all these problems.

**Bridge Over The Galindo River, Bilbao (2007)**

This bridge crosses the Galindo River obliquely at the confluence with the Nervión estuary, leaping cleanly over the stream and its riverside paths without intermediate support. It is laid out in a curve with a radius of 250 metres, 5% superelevation and a slope of 3%. The width is 27 metres with median strip and lateral footpaths 6 metres wide on the outer curve and only a metre and a half on the inner.
The solution chosen is an arch with a span of 110 metres and 16 metres high over a lower deck. This is the world's first spatial arch bridge with elevation curve and plan curve on a major structure. Near-horizontal braces anchored to cantilever ledges protruding from the inner edge of the deck are used to counteract the horizontal loads resulting from the plan curve. Thus the transverse loads are transformed torsion on the under-slung deck (Figure 22).

Every single component of this bridge - with the exception of the pedestrian walkway canopy - is designed in response to strict strength criteria. A complex strength problem has been converted into a beautiful new formal solution.

The bridge is supported on two abutments, has a pronounced plan curve and is composed of a steel and an out-of-plane spatial arch also made of steel. The box deck is 2 metres deep and 27 m wide with clearly curved edges. The 6 m-wide walkway is covered by a steel and methacrylate canopy not integrated into the strength calculations. The ribs that support the transversal braces that sustain the arch are arranged on the opposite sidewalk (crash barrier) (Figure 23).

The box deck is 100% steel with plate thicknesses of 15, 20 and 30 mm distributed according to strength demands. It is provided with longitudinal and transversal stiffeners. Web stiffeners placed every 4.4 m provide the transverse stiffness and channels on the upper plates and double T profiles on the lower provide the longitudinal strength.

The arch has a second degree parabolic profile in elevation and its plan follows the curve of the deck. It is made of two pipes with a diameter of 1,219 mm and wall thickness of 50.8 mm joined on the upper and lower surfaces by 50 mm-thick horizontal steel plates.

The arch is joined to the deck at the abutments by four 90 mm longitudinal steel plates, at each end (Figure 25).

Union of the arch with the transversal braces and vertical struts or hangers is performed by 30 mm-thick transversal plates which fully traverse the arch and are joined to the vertical hangers (circular tubes measuring 193.7 x 19) on the one hand and the transversal braces made of 83 mm-diameter enclosed cables on the other. Full penetration was required to join the arch elements to these transversal plates. The arch sections between the vertical plates are straight, which greatly simplifies execution (Figure 25).
Construction was performed using four falsework towers with temporary pile foundations. The deck is divided into sections 22 m long and 5 m wide placed on the abutments and falsework by cranes. Once welded, the deck was then harnessed to continue the next components.

Placement of the arch was executed using four falsework towers with the same vertical alignment as the supports on the riverbed. The components were placed by cranes and welded to the previous section.

Load was taken up by the pseudo-horizontal braces progressively in three phases, working from the ends towards the centre. The bridge was released from external support towards the end of this operation. Load was applied to the vertical hangars by deformation as the support points of the provisional piles were removed and the active braces began to take up the load.

A canopy with an overhang of 8.19 m was added to the concave outer strip of the deck to support a roof made of smooth transparent methacrylate.

**Bridge Over The Ebro River In Logroño (2002)**

The Logroño bridge crosses the Ebro within the city itself. This fact conditioned two aspects: the pedestrian walkways needed to be generous and the design must propose innovative formal and engineering solutions. To achieve the latter condition we separated the walkways from the central body. This provided two advantages: it reduces traffic noise for the pedestrians and creates a spatial structure defined by the hangers that support the inner edge of the walkways (Figure 26).

The Logroño bridge maintains a straight deck but the pedestrian walkways are split off. The bridge has a span of 140 m. To withstand the weight of the traffic the deck is composed of a trapezoidal composite...
beam 18.6 metres wide and 2 metres deep. The steel lateral decks that form the walkways are 4 m wide at the upper face and 2 m at the bottom with a depth of 1.1 m (Figure 27).

The arch is composed of twin 1.2 m pipes that bifurcate as they approach the deck to acquire the strength required to withstand the out of plane flexure when only one walkway are load. This would otherwise cause considerable transversal deformation of the arch and thus a significant vertical deflection of the walkways. However, this transversal stiffening of the arch was not sufficient on its own. The last four braces from the arch are anchored to the abutments, providing the arch with the required transversal stiffness (Figure 28).

The bridge was constructed by incremental launch of the central steel deck over falsework piles installed in the river and subsequently concreting the upper slab. The exterior walkways were then assembled from the central deck.

**Walkway over the Ebro river for the Zaragoza Expo (2008)**

Cable-stayed walkways are especially spectacular and economical solutions for very large spans (in this case 141 and 94 metres). They are also especially suited to adopt straight or curved plan layouts and to control the play of geometric forms that can be obtained with the hangers. The formal and aesthetic result is very attractive when the plan is curved and the pier inclined. This effect is reinforced at night with lighting directed at the hangers and piers, producing a striking curtain of light. Combining all this with adequate ground lighting and the use of an attractive colour for the hangers and piers produces a breathtaking effect, extremely suitable for cases like this (Figure 29).

The walkway plan is curved, the width no more than 4.5 m and the deck is suspended from an intermediate pier situated on the riverbank. The total length is 235 metres, 141 over the riverbed and 94 at the flood span. The axis is curved with a radius of 230 metres for the first 188 metres from abutment 1 and straight for the remaining 47 approaching the left bank. This deviation from the original constant radius is to prevent the hangers next to abutment 2 from intruding the pedestrian transit area (Figure 30).

There are certain specific features.

- The box deck is 100% steel, 4.5 m wide and 1 m deep.
- The upper slab is also steel, in this case on a single
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horizontal plane, and the lower slab is curved with a radius of 3 metres. The plate thicknesses are moderate, varying from 12 to 15 mm on the 94-metre span and reaching 30 mm on the span over the river, with the exception of the 5.9 metres next to the abutments where they are considerable, reaching 50 mm. It was necessary to stiffen the outer cell on the hanger side which was thus divided into two by a horizontal plate with a thickness of 16 mm. Both the upper and lower plates are longitudinally stiffened with T profiles.

- The box deck is suspended by hangers from the tower attached to one edge only, the inner side, so that the user has an unobstructed view of the Expo.

- The strength problem deriving from suspending the deck from one side only is solved by the curved deck plan, which converts torsion into flexure.

- The pier-tower is inclined. It is 90 m long, 78 m high with respect to its embedding point in the concrete and is inclined 30° with respect to vertical. The cross-section is circular and the radius varies from 1.1 m at the base to 0.9 m at 79.5 m high. From this point until the tip at 90 m the diameter diminishes to finally reach zero. Plate thickness varies from 40 mm in the main body, to 25 mm at rest.

**Príncipe De Viana Bridge Over The Segre River In Lleida (2010)**

This is a cable-stayed solution - an extradosed cable-stayed bridge - comprised of three spans of 35.85 m + 86 m + 75 m (Figure 32).

The useful width of the deck is occupied by two 4 metre-wide lateral walkways and two 6.6 metre-wide central carriageways, comprising a total useful width of 21.2 m and an overall width of 22.70 m.

The main (cable-stayed) section is 161 m long (86 m + 75 m) and the secondary bridge is a 35.85 m x 22.7 m concrete slab over the Avenida del Segre.

The main section consists of a U-shaped box girder with a central web. The lower face is curved with a width equal to the three webs of 0.30 m and the height of the 2.13 m central web. This box girder was originally constructed as two V-shaped beams which adopt the final form when joined. The constructor considered that these girders were too short and requested their replacement by a box girder constructed in situ.

Lightened, rectangular transversal plates with a width of 3 metres and thickness of 0.4 m with 30 cm lateral ribs were coupled to this girder. Once joined they form ribs of 60 x 40cm.

7 cm-thick floor slabs are placed over this structure and the 20 cm-thick deck slab is then concreted in situ (Figure 33).

The pier consists of four diverging arms: the deck is suspended from two of these and is supported on the other two. The main piers are prefabricated and the other two are constructed in situ (Figure 32).

The foundation of this pier is a 21 m x 9 m x 3 m footing.

The vertical height of the inclined piers that support the hangers is 38.6 m. The transverse cross-section varies between a
rectangular sector of 2.4 x 3 m and a section composed of two rectangles of 2.4 x 2 m and 0.4 x 1.2 m. This second rectangle is designed to lighten the pier visually from the front view.

Above the deck there is a pier head some 8.75 m high and with variable width between 3.8 m and 4.8 m with a suitably curved widening at deck level to house the cables.

The brace cables consist of: cables 5 to 15: 12 strands; cables 2 to 4: 14 strands and cable 1 which connects to the abutment, 1 strand. All strands have a diameter of 0.6 m. The braces pass through the pier head with curve radii of between 3.25 and 6.05 m and are anchored there by friction and adherence to the steel through-bushings.

Eccentric devices are installed on the inner face of the pier to dissipate the outward flexure it develops (Figure 34).

The connection of the brace cable sheaths to the tower is achieved with a telescopic coupling which, however, prevents relative movements of the tower with respect to the braces. The connection of the braces to the deck requires a special structure to absorb the numerous loads that are present on this area.

The short arms that support the deck from below are 17.16 m long with lower dimensions of 3.6 x 1.3 m and upper dimensions of 5.1 x 0.93 m.

The deck is protected by an intermittent impost along its entire length, a railing and fenders and two expansion joints.

The walkways are perforated with tubes to house conduits. The entire bridge is painted white except the inner area between the ribs and the main girder, which are dark blue.

Calculation of the construction process was based on an evolutionary model that provided the loads to be supported by all the components of the structure over the entire construction process until completion.

All the elements composing the deadweight, walkways, asphalt, fenders, railings, imposts etc. were entered to this model.
The main bridge over the Danube river is 1,391 metres long. It is composed of three types of deck depending on the length of the span involved. The road bridge incorporates spans of 80 over the non-navigable part and 3 spans of 180 m over the navigable channel. The rail bridge has a 40 m span with intermediate supports at the span quarters of the 80 m road bridge. The span distribution is: 52.0 + 7 x 80.0 + 124.0 + 3 x 180.0 + 115.0 m. The deck is a single box with transversal concrete brace struts. The box girder is 31.35 m wide and 4.5 m deep (Figure 35).

The cross section fulfils the project requirements. It consists of two independent 7.5 metre-wide double-lane carriageways. The pedestrian walkway and bicycle lane on the right side of the bridge is 2.5 m wide while the one on the left is 0.75 m, with additional space for traffic signals, electrical installations and maintenance. There are various safety barriers.

The single box girder has a 7.2 m lower slab with variable thickness between 0.45 m and 0.75 m. The webs are 0.50 m wide, increasing to 1.3 m above the piers. To complete the cross section there are two groups of inclined transversal struts situated every 4.3 m on the 80 metre spans and every 4.186 m on the 180 m spans to support the wings of the upper slab.

Construction of the central box of the 180 metre deck was performed using balanced cable-stayed cantilevers composed of precast segments 4.186 m long raised from the pontoons on the river by a mobile crane. The rest of the cross section was concreted in situ using a special mobile carriage sliding along the deck (Figure 36).

The 80 m spans were constructed using the balanced cantilever method on a launch beam. Each segment measures 2.15 metres.

The cable system was designed as an extradosed structure which required a significant reduction in the stress oscillations deriving from overloads. Therefore the following design parameters were adopted:

- Relatively low towers, around 1/10 of the span length or 19 m high for a span of 180 m.
- An extremely stiff deck: deck depth of 4.5 m, considerable when compared to classical cable-braced bridges. For example, the bridge over Cadiz Bay has a deck depth of 3 m for a span of 540 m.
- Two options were considered to limit oscillation of loads on the cables: variable deck depth and longitudinal struts. The latter is much more effective.
Saddles on the towers to accommodate the cable system.

Short cables: the longest measures 90 metres.

This reduction in the range of loads increases the fatigue resistance of the cables. External prestressing systems and simple saddles can be used at the top of the towers.

These specifications provide cost savings in construction and maintenance alike.

To protect the piers from the impact of shipping a grid consisting of precast vertical components with holes to accommodate cast in situ horizontal beams which join the precast parts was designed. The pile caps are situated at 36.60 m, well above the river’s emergency high water mark. The foundations were designed to withstand the impact of loads in accordance with Part 7 of Eurocode 1.

The railway access viaduct has a total length of 400 m. The span distribution is 32 m + 9x40 m + 8 m. It consists of a viaduct that crosses the roadway on the embankment to reach the central axis of the cross section of the main bridge.

The deck is a double box with a reinforced concrete transversal slab. The solid girders have a rectangular cross section with a depth of 1.9 m and width of 1 m. The slab is 0.25 m thick. Total width is 8.6 m. The cross section complies with the project specifications: a railway with a width of 6 m, two lateral 0.75 m maintenance walkways and 0.8 m for the electrical installation. The deck was constructed span by span using a scaffolding supported on the ground. Both the pretensioning and passive reinforcement were especially adapted for this construction process.

**Bridge over Cadiz Bay (2014)**

The bridge itself can be divided into four different sections depending on their function (Figure 37).

Total length is 3,082 m, by far the longest bridge in Spain and one of the longest in the world.
The deck is 34.3 m wide and accommodates four 3.5 m-wide traffic lanes (two in each direction), two tram lines and the sidewalks, fenders, brace cable housings and shields to protect traffic from the wind required to ensure that the bridge fulfills its objectives.

This deck had to be light, aerodynamic and slim, so a mixed steel and concrete structure with a depth of 3 metres and carefully profiled edges was adopted.

The access viaduct on the Cádiz side is 570 m long and reaches the main bridge. This part extends from Cádiz to the removable bridge section (Figures 38, 39 and 40).

Removable section with a length of 150 m.

The main bridge is a cable-stayed bridge with adjacent spans over the navigation channel. Length 1,180 m.

The construction method is by balanced cable stayed cantilever. The deck is divided into 20-metre segments, each of them assembled on the Muelle de la Cabecera and floated to the bridge where they will be hoisted by mobile cranes located on the nose of the cantilever (Figures 41 and 42).

Once hoisted they will be welded to the existing section and the cable installed from the tower. The top slab will then be reinforced and casted and the cable stays prestressed.

The access viaduct part from the Puerto Real side has a total length of 1,182 m.

It can be divided into three subsections: The subsection to the cable-braced bridge consists of three spans of 75 m with the same cross-section as the access from the Cádiz side but constructed of pretensioned concrete. The piers of these two access viaducts are identical (Figure 43).

The second subsection has the following spans: $75 + 68 + 4 \times 62 + 54$ m.

This second subsection is made necessary by axial traffic under the bridge...
and the presence of accesses to factories established along the viaduct route. This constraint entails design of frame piers with a free span of 13.5 m between uprights. The shape of all the components depends on the general design of these piers. The double trapezium, the usual form of the standard piers, is separated in this case with one trapezium for each frame column, which have a large base of 3.2 m, a smaller base of 2.9 m and a depth of 3 m (Figure 44).

These piers have two support arms at the top as in the rest of the spans. The height of these piers varies between 13 m and 34 m.

The deck is exactly the same as that of the previously described subsection.

The third subsection, next to the abutment 2 in Puerto Real, changes. The span changes to the standard of 40 m and the one next to the abutment to 32 m since the height of the piers descends rapidly on approach to the abutments.

Construction of the Puerto Real access viaduct is performed span-by-span, with joints situated at the span quarters and supported by scaffolding from the ground.

The entire width is supported on a single pier. Pier height varies between 8 m and 52.5 m, but all have the same shape regardless of the height. The double rhomboid is 10.5 m wide at the base of the highest pier and tapers to 4.2 m at the waist, where it once again widens to 10.5 m. The transversal dimension is 4 m at the centre and 2.9 m at the edge. Therefore the surface is warped.

Figure 42. Bridge over Cadiz Bay. Project drawing and construction.

Figure 43. Bridge over Cadiz Bay. Project drawing for the first subsection.

Figure 44. Bridge over Cadiz Bay. Project drawing for the second subsection.
Highway junction evolution in Spain. A guidebook for the design of highway junctions

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ABSTRACT

The rules for designing highway junctions (intersections, interchanges and roundabouts) in Spain since the 'sixties are reviewed. These rules have been scant for the big development in highway construction in the same period. A description is given of the development of the Guidelines for Highway Junctions, which have been introduced by a Circular Order of the Highways General Directorate in December, 2012: an endeavor of no small scope. The author of this article has acted as main Rapporteur for its text.

A description follows of the aim guiding the text of this new Guide, which strives to state the degree of binding carried by each of its provisions. The importance of operation is also stressed, human factors and driving aids; the latter must be taken into considerations from the very inception of the design. Two levels-of-service and seven design vehicles have been used as design criteria.

The operation of the junction has been taken into account in detail, including interactions between contiguous junctions and the needs of special users (heavy goods vehicles, vulnerable users and transit). Starting from an analytical approach, a set of possible functional morphologies has been synthesized; and a method has been established for selecting the most suitable junction for a given case. Some details of the Guide, which are a relative novelty, are also examined.

Key words: Geometric design, Intersections, Interchanges, Roundabouts, Signals.

Introduction

Believe it or not, up to five months ago most of the material about highway junctions published by the Highways General Directorate of the Spanish Ministry of Development was more than four decades old, when the Directorate’s name included the Neighborhood Lanes and it depended from the Ministry of Public Works:

- In 1962 a Circular Order\textsuperscript{i} published a Technical Rule detailing the geometric design of the elements of an intersection.

- In 1965, for the II Traffic Seminar a set of intersection examples was published.

- In 1967 these documents were updated into Recommendations for the design of intersections\textsuperscript{ii}; a second edition\textsuperscript{iii} was made in 1975.
In 1968 Recommendations for the design of interchanges were published. These documents were a fortunate translation of analogous ones by AASHO; and with them and their wits, Spanish engineers designed and built many and diverse highway junctions in our network. Small wonder, though, that many deemed them obsolete.

It is true that, when the roundabouts came along, in 1989 some Recommendations on roundabouts appeared: a version that the late Eng. Gullón and myself made of the equivalent British ones, to provide a technical framework for a new type of intersection which has known a great fashion since.

These topics were also affected by:

• La 8.2-IC Standard on highway markings.

• Regulation of access to State highways, frontage roads and services for motorists, by a Ministerial Order of 1997, which affected several topics concerning junctions: namely the distance between adjoining ramps, and regulation of cross movements in a single-carriageway highway.

• The 8.1-IC Standard on signing.

The various documents which tried to revise, at the beginning of the ‘nineties, the 1964 Geometric Design Standard 3.1-IC and the 1976 Complementary Standard for Freeway, dealt in a more modern way with junction design. Lastly, when the 1964 GDS was at last updated in 1999, certain aspects of junctions were modified, such as speed change lanes’ length; and it was decided to include a short Chapter (No. 8) concerning junctions, only brushing some general ideas and basic prescriptions. Only some decisions were taken concerning:

• Junction type: in divided highways only interchanges would be used. Junction type in non-divided highways would be determined after a specific study.

• Connections to ramps and turning lanes: only other ramps and/or turning lanes would be allowed, but no collector – distributor roads, and even less frontage roads.

• Distance between adjoining ramps, on the line of the 1997 regulations, but with some contradictions.

Thus, specific regulations concerning highway junctions were left for a better occasion. The text of 3.1-IC, included in a high-rank regulation, is very binding for later regulations of lesser rank. Luckily, article 1.2 of 3.1-IC allows exceptions and changes in its criteria, maintaining in any case the due safety con-ditions, but avoiding out-of-proportion spending. This is the case, namely, of urban highways, mountain roads, highways through natural settings of high environmental value or fragility, and local improvements of existing highways.

It was clear, therefore, that the 3.1-IC Standard dealt basically with rural highways and freeways with a new alignment, in an environment in which the population was not intensive and therefore so were space restrictions, approved planning constraints, and traffic demand.

Things being so, at the end of 1998 the Highway General Directorate called an open consulting tender to write Guidelines for the design of highway junctions, in which the profitable concepts of preceding documents would be systematically integrated with the most modern available regulations, recommendations and advices of the technique, so that the design and later operation of highway junctions could result in economical, safe and environmentally integrated infrastructures.

I led the team who won the tender; after preparing a draft of the Guide, this was circulated to a Steering Committee nominated by the HGD. I was Rapporteur to this Committee all along some 50 meet-ings, in which a very lively debate was carried out. After taking into account their opinions, I wrote the final draft of the Guidelines for Highway Junctions, published on December 14, 2012 by the Circular Order 32/2012 of the HGC: a book of some 550 pages.

The Spirit of the Guide

The Guidelines for Highway Junctions (GHJ) is a document much more didactic than a standard regu-lation. It provides advice for designing highway junctions, both new and retrofit; it shows possibilities for solving the actual problems of each case, and includes the most substantial part of the State of the Art.

To this end, in the GHJ text one can find text with various degrees of binding:

• Rules which must be followed in any circumstance, except defined exceptions foreseen in themselves.
• Guidelines: instructions to be followed unless there is justification enough.

• Recommendations: non-compulsory advices which is interesting to follow, since a good effect is expected from them.

• Suggestions: commonly accepted ideas which can be followed, from which also a good effect is expected.

• Possibilities: ideas which can be followed for lack of anything better, from which a good effect is believed to derive.

• Comments: explanatory text so concepts are more easily understood.

The GHJ has been written placing a paramount role for junction operation, especially safety and layout understanding. To this end, driver characteristics have been taken into account, and criteria of simplicity, uniformity and consistency have been established.

Basic Concepts

The GHJ has a certain 3-D outlook, including not only the layout of the highway elements but also their dynamic effects on operation, i.e. in the behavior of drivers and other users. This is not as straightforward as things related to the layout of alignments, grades and cross-sections; but rather to the communication between drivers and the highway and its junction, the purpose of which is to make clear, to simplify, to regulate and to make easy the driver’s task.

Thus, to the usual criteria others have been added resulting from human factors research, related to characteristics and expectations of drivers about the highway layout and the devices which control traffic on it. Design and signing of a highway junction must be tempered the results of experience in operating similar junctions, seen from the standpoint of actual users (customary or sporadic, cross or worried), who must be able to use the junction with ease and fluidity but mostly with safety, without worries, doubts nor frustrations. The perception of the junction must not give rise to hesitations, half-maneuvers, not even on the part of those not familiar with it; their task must me made easy if it is correct, and hampered in the contrary case. Even so, if a mistake is made, the junction must be “forgiving”, not exacting a high price for one moment of distraction or indecision.

It is necessary to call the drivers’ attention to what should be done, instead to what should not be done. Those designing and signing highway junctions must make easy the drivers’ task, instead of bewildering them in an environment already too complicated. Traffic regulation and, especially, signing must be taken into account from the very beginning of the design, not merely added at the end. De-sign should cater for unfamiliar drivers, relatively tyros, and take into account their likely mistakes.

Design Criteria

In the elements of a highway junction two level-of-service have been considered for the design year:

• A normal acceptable LOS in the design hour, for which drivers can be guaranteed to enjoy relatively easy driving conditions.

• An extraordinary LOS in the peak hour, for which circulation in some of the junction elements can turn unstable(a), and the probability of a breakdown is higher than 50 percent.

The GHJ defines seven standard vehicles, their dimensions, maneuverability and performances, and their application domains. Twelve interactions between them are also analyzed: six of them belong to sections, and the other six are specific to junctions.

Junction Operation

The GHJ analyzes the operation of junctions, according to the following criteria:

• Flow regulation in cross movements: priority to the right, fixed priority, sequential priority (signals), rotary flow and non-level crossing.

• Operation of on- and off-ramps, bifurcations and confluences: upstream, in the disturbed zone, and downstream.

• Congestion in a ramp due to an intersection at its end.

• Weaving sections, of which three types are defined and analyzed, both their operation and the possibility of improvement.

(a) Even if flow stays stable on the highway sections, far from the junction.
Emulsionantes:  
**ASFIER** 
Activantes de adhesividad:  
**ASCOTE** 
Aditivos:  
**PLASFALT** 

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Design speed is related to operating speed, refining the concept of design speed defined in the 3.1-IC Standard and keeping the concepts of specific speed and planning speed. As specific to junctions the relative speed of conflicting vehicles is dealt with.

For the key topic of interactions between adjoining junctions, which determines the minimum distance between them, a distinction is made between motorways / freeways and other highways, and between rural or urban environments.

Lastly, several measures are described to accommodate special users: heavy goods vehicles, vulnerable users and transit.

**Analysis, Synthesis and Selection**

A classical method for studying a complex reality, such as that of the highway junctions, has been followed in the GHJ:

First, all elements which can be part of a highway junction have been analyzed:

- **Legs:** number and layout.
- **Possible movements from each entrance:**
  - Through movements:
    - Geometric design
    - Continuity
    - Equilibrium at on- and off-ramps
    - Non-level crossings
    - Speed
  - Right turns:
    - Layout
    - Channelisation
  - Left turns:
    - Layout
    - Central wait lanes
- **Geometric design:**
  - Alignments
  - Grades
  - Coordination
  - Platform cross-section
  - Roadside
- **Sight distance**
- **Traffic islands**
- **Speed change lanes and wedges**
- **Connections (on- and off-ramps):**
  - Definitions
  - Placement
  - Side
  - Number de lanes and layout
  - Order and distances
- **Bifurcations and confluences**
- **Non-permitted movements**
- **Frontage roads**
- **Collector – distributor roads**
- **Central and lateral carriageway systems**
- **Median treatments**

Those elements are then combined in different shapes which are not only described, but also criticised, stating their advantages and drawbacks in view to select the most suitable one.

- Three-leg intersections with fixed priority: T, Y.
- Four-leg intersections with fixed priority: cross, X.
- Roundabouts; normal, mini-, double, barbell.
- Semaphore-regulated intersections and roundabouts.
- Three-leg interchanges:
  - Non-directional: trumpet, semidirectional
  - Directional
- Four-leg interchanges:
  - Only one structure: diamond, partial cloverleaf, full cloverleaf
  - More than one structure: non-level roundabout, shaft, modified cloverleaf

The selection process is completed with a functional analysis of the selected solutions.

**Some Particularities of GHJ**

In the following paragraphs some topics, frequent in Spanish practice, are described that the GHJ has tackled to achieve a better understanding of junctions by drivers, taking into account a viewpoint base o highway systems engineering and in communication between the infrastructure and its users.
• Route continuity: a highway having a number or a name must be easy to follow through the junction, especially for non-familiar users. These problems arise often in suburban areas, and are related to defects in the hierarchy of the highway network.

• Equilibrium of the number of lanes: at an off- or an on-ramp no more than one lane can be lost or gained. If the ramp, because of its high flow, has to have more than one lane, one or more lanes should be added to the highway for a rather substantial distance. Besides the usual layouts for a single lane (Fig. 1), the GHJ also studies layouts for two lanes (Fig. 2). The detail includes signing and marking, which are both specific for each layout.

• Placement of connections: most drivers unfamiliar with a junction expect to find a single off-ramp before the crossing, and a single on-ramp beyond. Placing the exit on a curve instead of on a tangent goes against the perceptibility of its presence and the understanding of its function. By anticipating the exit, close to the main highway, it can be placed on a tangent and before the crossing, where it can be perceived from far enough, and its function can be understood even by unfamiliar drivers.

• Connection side: drivers expect that flows exiting from their right side, or entering on their right side, are less important than their own (through movement). Entrances and exits on the left cause a non-regular, unsure operation, except where it is a bifurcation or a confluence.

• Distance between connections: it has been necessary to delve more deeply in the operation (in terms of LOS) of the various connection sequences which cannot be considered isolated: two consecutive off-ramps, two consecutive on-ramps, an off-ramp after an on-ramp, or an on-ramp after an off-ramp. It is a very important topic, because not only it has influence on the minimum distance between adjoining junctions, but also some lay-outs cannot be solved without recourse to collector – distributor roads which prevent weaving on the main carriageway. The problem can be also had outside this latter, in ramps sharing more than one destination or origin, or in the collector – distributor roads themselves.

• Design speed of the alignment elements, which has to take into account that in a junction operating speeds are very different from those on the connecting legs.

• Reference point for the alignment: in a junction, assuming that vehicle trajectory is well enough represented...
ted by the alignment does not give enough approximation to the operating conditions (Fig. 3). Trajectories, referred to the center of the steering axle, are indeed what must follow the usual tangent, circle and spiral shapes; and not the edges of the ramps and/or turning lanes, which anyway can be derived from the trajectory (Fig. 4).

• Sequence of alignments: in a ramp, non-regularity in curvature variation, very easy to incur into, usually causes a higher-than-average accident rate.

• Grade of ramps: since they are much shorter than main carriageways, steeper grades can and must be used in them.

• Simultaneous design and signing of the junction: How a junction is going to be signed is a very important constraint on its initial design.

OTHER CHAPTERS

The GHJ also includes some other Chapters completing design and operational details of highway junctions:

• One concerns the particularities of improving or retrofitting existing junctions.

• Another Chapter deals specifically with traffic safety, explaining concepts such as risk, favorable or unfavorable design features, and more frequent accident patterns for each type of junction. Vehicle contention systems are discussed which are adequate for junctions.

• Another Chapter describes in detail the driving aids: signing, marking (as a complement to existing Standards, now under revision), signals, and lighting (Figs. 5 y 6).

• In another Chapter the baselines of signal regulation are explained.

• There is a last Chapter on topics related to landscaping and blending with the environment.

The GHJ also includes a complete Glossary, and several Annexes develop concrete topics the inclusion of which in the main text would have hindered its understandability.

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Figure 5. Channelizing markings in a two-lane roundabout, and the resulting trajectories.

Figure 6. Signing of a type 2-BP off-ramp.

This diagram does not show all vertical signs or all road markings.
Quality in public transport services for promoting a sustainable mobility: Case study

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ABSTRACT

Private vehicle is still the dominant mode of transport in motorized trips carried out by citizens, in spite of being the most inefficient and pollutant of all. Improving the quality of public transport services can produce a modal shift towards this more sustainable modes of transport. In this research and using data from customer satisfaction surveys, we applied decision trees for analyzing the service quality of the metropolitan public transport of Granada (Spain), in order to define transport strategies that leads towards a higher level of quality of the service and, consequently, more satisfied passengers. This analysis is developed for the overall sample of users, but also for segments of passengers with more homogeneous opinions about the service. The stratification is performed according to passengers’ travel reason. This stratification allows to formulate more personalized guidelines of improvement and not generic ones.

Key Words: Service quality, Public transportation, Customer satisfaction survey, Passengers’ perceptions, Decision trees.

INTRODUCTION

Currently traffic congestion, stress, atmospheric pollution, noise, parking limitations, etc. are some of the main problems generated by the massive use of the private vehicles in the cities. There is a high dissatisfaction among citizens, in addition to the environmental and energy consumption problems set off by this situation. Practically all Public Transport Administrations acknowledge about this and they are trying to promote more sustainable modes of transport as an alternative to the private vehicle. One of the principal measures for reaching a sustainable transportation in the cities consists on attract a higher number of citizens towards the use of public transport modes, by offering a high quality service. Service quality, which is related to a serie of variables or attributes describing the service, will...
condition the selection or not of a transport mode. If it is possible to identify which are the variables that are more closely related to the quality of a service, this will help the administration to decide where they have to invest their resources for improving this quality.

Along a great amount of time, the evaluation of service quality in public transportation was carried out from the manager perspective (transport operators and government), based on the efficiency and effectiveness service and operations costs. However, in the last years, researchers and transport managers have started to think that passengers’ point of view is the most relevant perspective for evaluating the service performance. The UNE-EN 13186 standard defines the quality of service in public transportation of travelers considering two different points of view: on the one hand the administration and operators point of view and, on the other hand, the passengers point of view (current and potential passengers). Analyzing both perspectives together can offer a very detailed information about the performance of the service. Nevertheless, which it is really important for transport agencies is to know what passengers think about the service they are providing. Therefore, perceived quality becomes a powerful tool that helps public transport managers to supervise, evaluate and implement improvements in the service. Currently, customer satisfaction surveys is the main way of collecting passengers opinions about the service.

There are different techniques that can be used for determining which are the service variables with the highest influence over the overall service quality. Asking customers to rate each attribute on an importance scale is the method mostly used by the operating companies. On the contrary, derived importance methods which determine the importance of the attribute by statistically testing the strength of the relationship of individual attributes with overall service quality present a great number of benefits.

However, most of these techniques, such as regression models, structural equation models, or discrete choice models, used for deriving the importance of the attributes on the passengers’ perceived quality have their own model assumptions and pre-defined underlying relationships between dependent and independent variables. If these assumptions are violated the model could lead to erroneous estimations of the likelihood of quality of service.

Decision Trees is a powerful tool for transport planners, not only because they do not have problems due to the violation of any assumptions (they do not pre-decide underlying relationships between the dependent variable and the independent variables), but also due to their results provide great practical utility for public transport agencies. The outcomes of the models are simple, easy of understanding because of their graphical representation and they are able to derive the importance of the variables. Moreover, useful decision rules can be extracted of these models. This technique has been successfully applied for analyzing service quality in public transportation by de Oña et al. and de Oña and de Oña. In the first study the authors adopted decision trees methodology for identifying the key factors affecting the quality level of a bus service operating in Granada; while in the second study, the quality of a rail service in the North of Italy was analyzed.

Then, once the most influent variables over the overall service quality are identified, the competent administrations could formulate more efficient and effective strategies for improving service quality, and consequently passengers satisfaction. However, for achieving a successful quality police, it is not recommendable to develop general actions for all the passengers, because their opinions are very heterogeneous among them. This heterogeneity presented in passengers’ opinions is one of the big problems of analyzing service quality. This heterogeneity is due to different factors, such as the qualitative nature of PT service aspects, the different attitudes of passengers towards the use of PT services, the users’ socioeconomic characteristics, the diversity in tastes, even the same user could change its opinion depending it has reflected or not which are the characteristics that describe the service.

In the course of the time, managers and operators of public transport services have focused their actions and performed their marketing advertising towards the global population (mass marketing), without paying attention to specific groups of passengers. However, it is proved that this way of designing policies and advertising it is not very effective. Some authors have decided to stratify the population according to simple segmentations, such as the age, gender, travel reason, and so on. This represents a solution to the generic approach carried out by the service managers. Stratifying the sample of users will permit that transport planners lead their strategies and interventions towards specific segments of passenger, using a personalized marketing.

In this paper, an analysis of the quality of the Granada’s metropolitan public transport service based on
passengers’ perceptions is presented. The main objective of this analysis is to extract powerful guidelines of performance for transport planners, in order to promote a more sustainable mobility in this city and its metropolitan area. Decision trees methodology, and specifically the Classification and Regression Trees (CART) algorithm, has been used for this purpose due to its useful and very informative results (importance of the variables, decision rules, etc). Moreover, in order to determine personalized marketing strategies, this analysis has been developed for the overall market of passengers, but also over three different segments of users stratified according to their reason of travelling.

The present paper is divided into five sections. Section 2 describes the methodology applied in the research work, Section 3 introduces the data used for the analysis, Section 4 discusses the results obtained from the different models built, and finally, in the last section, the paper concludes presenting the main conclusions of the study.

**Metodology**

The Classification and Regression Tree (CART) algorithm is a methodology for building Decision Trees developed by Breiman et al. This algorithm has the ability to develop either types of tree: a Classification tree when the target variable is categorical, and a Regression tree when the target variable is continuous. In this paper a Classification tree is used, because the target variable analyzed is categorical (overall evaluation of service quality: Poor, Fair and Good). Unlike other popular algorithms used also for building decision trees (ID3, C4.5, etc), CART methodology generates binary trees, splitting recursively the branches into two ways.

The development of a CART model generally consists on three steps: the tree growing, the tree pruning and selecting the optimal tree. The first step is the tree growing. The principle behind the tree growing is to recursively partition the target variable to maximize “purity” in the two child nodes. Then, this process begins with all the data concentrated on the root node. On the basis of an independent variable (splitter), the root node is divided into two child nodes. The variable used as splitter is the one that creates the best homogeneity in the two child nodes. In fact, the data in each child node are more homogeneous than those in the upper parent node. The splitting process is applied recursively for each child node until all the data in the node are of the same class (the node is pure), their homogeneity cannot be improved, or a stopping criterion has been satisfied. In this case, terminal nodes are created.

Then, during the tree growth, a set of candidate split rules is created for the recursively partition of the target variable. These set of candidate split rules are evaluated and ranked using a splitting criteria based on the Gini index. The Gini index measures the impurity degree of a node in a tree. This impurity may be defined as follows:

\[
\text{Gini} (m) = 1 - \sum_{j=1}^{J} p_j^2 (j|m) \tag{1}
\]

Where Gini (m) is the impurity measure of a node m, J is the number of classes of the target variable, and \( p_j(m) \) represents the conditional probability of an instance to belong to the class j when it is in the node m. This probability is defined as follows:

\[
p_j(m) = \frac{\pi_j N_j(m)}{N_m}
\]

\[
p(m) = \sum_{j=1}^{J} p(j,m) \tag{2}
\]

Where \( \pi_j \) is the prior probability of the class j, \( N_j(m) \) is the number of instances of the class j in the node m and \( N_j \) is the number of instance of the class j in the root node. If a node is ‘pure’ (all the instances are of the same class), this measure (Eq. 1) will reach the minimum value equal to zero. On the other hand, the less homogeneous are the nodes, the value of the Gini index will be higher.

Then, the splitting criterion, denoted as the Gini Reduction criterion, measures the “worth” of each split in terms of its contribution toward maximizing the homogeneity of the child nodes through the resulting split. If a split results in splitting of one parent node into B branches, the “worth” of that split may be measured as follows:

\[
\Delta \text{Gini}(x_j,T) = \text{Gini}(T) - \sum_{b=1}^{B} P(b) \text{Gini}(b) \tag{3}
\]

Where \( \Delta \text{Gini}(x_j,T) \) represents the Gini Reduction measure at a parent node T which is split by a variable xj. \( \text{Gini}(T) \) denotes the Gini index (impurity) of the parent node T, \( P(b) \) denotes the proportion of instances of the parent node assigned to the child node created with the branch b, and \( \text{Gini}(b) \) is the Gini index of the child node created with the branch b. So, considering the definition of the Gini Reduction criterion, a split resulting in more homogeneous branches will have a higher value of the “worth” or Gini Reduction.

Following the splitting criterion process until no more partitions can be created, the terminal nodes are created and a saturated tree is obtained. The saturated tree provides the best fit for the data set which it is
constructed from, but overfits the information contained within the data set. This overfitting does not help in accurately classifying another data set. Now, to lessen the complexity of the saturated tree that overfits the learning data and to create simpler trees, the tree is “pruned” in the second step. This pruning is performed according to the Cost-Complexity algorithm, which is based on removing the branches that add little to the predictive value of the tree. After pruning a branch, if the increase in the misclassification cost is sufficiently lower than the decrease in the complexity cost, that branch will be pruned, and a new tree is created. As more and more nodes are pruned away, simpler and simpler trees are the result.

The last step is to select an optimal tree from the pruned trees. The principle behind selecting the optimal tree is to find a tree with respect to a measure of misclassification cost on the testing dataset (or an independent dataset), so that the information in the learning dataset will not overfit. When the tree grows larger and larger, the misclassification cost for the learning data decreases monotonically, indicating that the saturated tree always gives the best fit to the learning data. On the other hand, in the misclassification cost for the testing data, first there is a decrease, and then an increased is observed, after reaching a minimum. Then, the optimal tree is the one that has the least misclassification cost for the test data. More detailed description of CART analysis and its applications can be found in Breiman et al. (XXVII).

One of the most valuable outcomes provided by CART analysis is the value of the standardized importance of independent variables, which reflects the impact of such predictor variables on the model. The information is obtained for all the independent variables, making it easy to find which ones are the most important.

**Data**

Granada is a medium-sized city in the southern Spain with a population of around 500,000 inhabitants in the metropolitan area. A Granada Area Transport Consortium was created in 2003 to coordinate bus service management in the Metropolitan Area. The PT service in the metropolitan area carries more than 10 million passengers every year. It is provided by a bus system in which 15 bus companies operate in 18 independent transport corridors linking the metropolitan municipalities with the centre of the city of Granada.

The lines network is established by a radial structure focused on two central areas of the city of Granada, one in the north and the other one in the south of the city, and extending in all directions (corridors) to the rest of the urban agglomeration. Owing to the fact that Granada municipality population represents almost half of the total population in the metropolitan area, and also
the main trip generators centers are located there (such as administrative centers, health centers, educational and commercial centers), the structure of the transport system has been generated with this shape.

Since 2003, various improvements have been implemented by the Transport Consortium in the metropolitan transport system. These improvements involve establishing an Integrated Fare System, increasing the number of service a day, creating new services in areas of urban growth, etc. Moreover, in 2006, the Transport Consortium conducted the first CSS to evaluate Service Quality in the Granada Metropolitan Public Transport system. Since this year, it has developed an annual CSS to analyze changes in the perceived Service Quality of the passengers. Each year more than a thousand users are interviewed in the months of March or April. The interviews are conducted through a face-to-face questionnaire proposed to the users at the main bus stops of the lines.

The data used in this paper are those collected in the CSSs carried out between 2008 and 2011. In order to stratify the sample of users in segments of passengers with high representation, the data of these four surveys are jointly analyzed.

The questionnaires were structured into two main sections (see table 1). The first section gathered general information about the service (e.g. operator, line, time of the interview, origin destination), demographic characteristics of the users (e.g. sex, age, occupation) and their travel habits (e.g. reason for travelling, frequency of use, type of ticket, availability of a private vehicle, complementary modes used for access to/ moves from the bus stop).

The characterization of the sample across the years under study is represented in table 2. In general, the samples are characterized by a higher number of females than males. Users aged between 18 and 30 years old and between 31 and 60 years old compose around a 90% of the sample, and only the remaining 10% is older than 60 years old. More than a half use the service almost diary (4 or more times in a week), and about a fifth of the sample take the bus frequently (from 1 to 3 times a week). The rest of the respondents use the bus with an occasional or sporadic frequency (more or less than once a month).

Concerning the purpose of the trip, passengers have different reasons for travelling. For about half of the respondents the main reason is reaching the work or study place. The other half stated that they travel for other purposes, such as doctor, shopping, holidays or other personal activities. The number of users that have available a private vehicle for making the trip is almost equally spread with the ones that do not have available a private vehicle, being these last group a little bit higher.

Most of the sample accesses to the bus stop and form the bus stop to their destination on foot, and the rest use other modes (e.g. car, urban bus, motorbike, Table 2. Sample Characteristics (CSSs for the period among 2008 and 2011).

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Male</td>
<td>28.19%</td>
<td>30.18%</td>
<td>28.93%</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>71.81%</td>
<td>69.82%</td>
<td>71.07%</td>
</tr>
<tr>
<td>Age</td>
<td>&lt;18-30 Years Old</td>
<td>51.21%</td>
<td>38.90%</td>
<td>56.09%</td>
</tr>
<tr>
<td></td>
<td>&gt;18-30 Years Old</td>
<td>48.79%</td>
<td>61.10%</td>
<td>43.91%</td>
</tr>
<tr>
<td>Use Frequency</td>
<td>Almost Daily</td>
<td>53.38%</td>
<td>48.11%</td>
<td>51.27%</td>
</tr>
<tr>
<td></td>
<td>Frequently</td>
<td>18.00%</td>
<td>20.44%</td>
<td>21.62%</td>
</tr>
<tr>
<td></td>
<td>Occasionally</td>
<td>14.13%</td>
<td>19.50%</td>
<td>15.43%</td>
</tr>
<tr>
<td></td>
<td>Sporadic</td>
<td>10.70%</td>
<td>11.95%</td>
<td>11.68%</td>
</tr>
<tr>
<td>Travel Reason</td>
<td>Occupation</td>
<td>29.68%</td>
<td>24.08%</td>
<td>27.80%</td>
</tr>
<tr>
<td></td>
<td>Studies</td>
<td>22.03%</td>
<td>22.07%</td>
<td>23.55%</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>48.29%</td>
<td>53.85%</td>
<td>48.65%</td>
</tr>
<tr>
<td>Private vehicle available</td>
<td>No</td>
<td>56.44%</td>
<td>54.96%</td>
<td>57.71%</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>43.56%</td>
<td>45.04%</td>
<td>42.29%</td>
</tr>
<tr>
<td>Mode origin/bus stop</td>
<td>Walking</td>
<td>67.61%</td>
<td>85.43%</td>
<td>70.61%</td>
</tr>
<tr>
<td></td>
<td>Vehicle</td>
<td>32.39%</td>
<td>14.57%</td>
<td>29.39%</td>
</tr>
<tr>
<td>Mode bus stop/destiny</td>
<td>Walking</td>
<td>89.60%</td>
<td>96.06%</td>
<td>90.71%</td>
</tr>
<tr>
<td></td>
<td>Vehicle</td>
<td>10.40%</td>
<td>3.94%</td>
<td>9.29%</td>
</tr>
<tr>
<td>Type of Ticket</td>
<td>Standard Ticket</td>
<td>40.22%</td>
<td>27.42%</td>
<td>22.83%</td>
</tr>
<tr>
<td></td>
<td>Consortium Card</td>
<td>52.68%</td>
<td>64.35%</td>
<td>64.63%</td>
</tr>
<tr>
<td></td>
<td>Senior Citizen Pass</td>
<td>6.59%</td>
<td>4.03%</td>
<td>6.63%</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>0.51%</td>
<td>4.19%</td>
<td>5.91%</td>
</tr>
</tbody>
</table>
bicycle, etc). Also information about the type of ticket used by the passengers was collected. Most part of passengers uses the Consortium card, another important group of users travel with the Standard ticket and only a little part of the sample uses the Senior citizen pass or another type of ticket.

The main change observed in the characterization of the sample over the years is that it is decreasing the use of the Standard ticket in favour of the Consortium card.

The second section of the questionnaire focuses on the users’ opinions about the service. This part is also divided in 3 main sub-parts: Part A, referred to the passengers’ perceptions about the quality of twelve attributes describing the service (see table1), Part B according to rank the importance of these attributes (only the three most important attributes), and Part C, collecting a global evaluation of the service quality.

An 11-point Likert scale, from 0 to 10, was used for measuring the perceptions of the twelve attributes describing the service and a 5-point semantic scale (Very poor, Poor, Fair, Good and Very good) was used for measuring the overall evaluation about the service quality.

Four different models are built using the CART algorithm. A decision tree for the overall sample, and three more decision trees built for segments of users created under the criterion Travel Reason (Occupation, Studies and Other reasons). All these four models were generated using as the target variable the overall evaluation of the service (EVALUATION) and various of the variables collected in the surveys as independent variables: demographic variables (2), travel behavior (8), and the perceptions of the twelve attributes describing the service (12). A total of 20 independent variables were introduced in the model for classifying the target variable. Moreover, the scale of the target variable was recoded in a reduced 3-point semantic scale in order to find more applicable decision rules.

The semantic scale comprised the rates Very poor and Poor as POOR, Fair equal to FAIR, and Good and Very Good as GOOD.

Results

Figure 1 shows the tree generated for the overall market. The root node (Node 0) is split into two child nodes (Node 1 and Node 2), using the variable that maximizes ‘purity’ in the two child nodes. In this case, the splitter was Information. When Information is rated with a score higher than 6 (Node 2), the overall SQ is likely to be perceived as GOOD (75.7%). 72.1% of the sample is concentrated in this child node (Node 2), which demonstrates that this factor is a great discriminant of the model.

The next best splitting criterion for those who scored Information with a value equal to or lower than 6 is Frequency. This is a key variable for discriminating user perception of overall service quality (SQ). It groups those who give a value of POOR or FAIR on the left side (Nodes
5 and 6), as opposed to those who rate it as GOOD or FAIR, on the right side (Nodes 8, 9 and 10). The cut-off point for Frequency is a value of 2. When perceived Frequency is very bad ($\leq 2$) and Proximity is considered insufficient ($\leq 4$), there is a high probability (69.7%) that the passenger will rate SQ as POOR. On the other hand, if the Frequency scores higher than 2 and Temperature has an adequate score ($>6$), SQ perception will be GOOD. When Frequency scores high enough ($>6$), a rating of GOOD is obtained even when the score for Temperature is 6 or lower. This tree is 68.56% accurate.

The trees generated for the three segments of users stratified by the travel reason criterion (Occupation, Studies and Other reasons) are very different from the tree generated for the overall market. In the following, these decision trees are displayed in the form of decision rules, and not as tree figures.

Decision rules are one of the most powerful outcomes extracted by decision trees. They provide very powerful information for transport planners and managers who, based on these rules, could formulate more adequate strategies. From each terminal node of the tree, it is extracted a decision rule. The decision rules developed for each segment of passengers are represented in Tables 3 (reason=occupation), 4 (reason=studies) and 5 (reason=other reasons).

Table 3. Decision rules extracted from the Decision Tree built for Occupation.

<table>
<thead>
<tr>
<th>NODE</th>
<th>RULE</th>
<th>THEN</th>
<th>ACCURACY RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>“Frequency” &gt; 6</td>
<td>Service is rated as “Good”</td>
<td>79.0</td>
</tr>
<tr>
<td>4</td>
<td>“Frequency”$\leq 6$ and “Information” &gt; 6</td>
<td>Service is rated as “Good”</td>
<td>59.1</td>
</tr>
<tr>
<td>5</td>
<td>“Frequency”$\leq 6$ and “Information”$\leq 6$ and “Frequency”$\leq 2$</td>
<td>Service is rated as “Poor”</td>
<td>63.6</td>
</tr>
<tr>
<td>6</td>
<td>“Frequency”$\leq 6$ and “Information”$\leq 6$ and “Frequency”$&gt;2$ and “Cleanliness”$\leq 6$</td>
<td>Service is rated as “Fair”</td>
<td>63.2</td>
</tr>
<tr>
<td>7</td>
<td>“Frequency”$&gt;6$ and “Information”$\leq 6$ and “Frequency”$&gt;2$ and “Cleanliness”$&gt;6$</td>
<td>Service is rated as “Good”</td>
<td>46.2</td>
</tr>
</tbody>
</table>

Table 4. Decision rules extracted from the Decision Tree built for Studies.

<table>
<thead>
<tr>
<th>NODE</th>
<th>RULE</th>
<th>THEN</th>
<th>ACCURACY RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>“Punctuality”$\leq 6$ and “Safety”$\leq 4$</td>
<td>Service is rated as “Poor”</td>
<td>64.3</td>
</tr>
<tr>
<td>4</td>
<td>“Punctuality”$\leq 6$ and “Safety”$&gt;4$</td>
<td>Service is rated as “Fair”</td>
<td>54.1</td>
</tr>
<tr>
<td>6</td>
<td>“Punctuality”$&gt;6$ and “Temperature”$&gt;6$</td>
<td>Service is rated as “Good”</td>
<td>74.9</td>
</tr>
<tr>
<td>7</td>
<td>“Punctuality”$&gt;6$ and “Temperature”$\leq 6$ and “Frequency”$&gt;6$</td>
<td>Service is rated as “Fair”</td>
<td>58.8</td>
</tr>
<tr>
<td>8</td>
<td>“Punctuality”$&gt;6$ and “Temperature”$\leq 6$ and “Frequency”$&gt;6$</td>
<td>Service is rated as “Good”</td>
<td>62.1</td>
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</table>

When the reason for traveling is Occupation (see Table 3), Frequency becomes the most discriminant variable, being the variable splitting the root node. The tree built produced 5 terminal nodes, and consequently 5 decision rules. Three of them predict a GOOD overall evaluation, one a FAIR evaluation, and only one node a POOR evaluation of the service. For example, the rule produced in the terminal node 4 states that IF Frequency is minor or equal to 6 and Information is evaluated higher than 6 THEN the overall evaluation of the service will be GOOD, with a probability of 59.1%.

This way of representing the results of the decision trees provides powerful information to transport managers who, focusing in these decision rules, could decide where to utilize their resources. For example, in the decision rule for node 4, they could decide to improve the information if reaching a higher quality of the frequency is very costly.

By observing the results for the other two segments of passengers, when the reason for traveling is Studies (see Table 4), the most important variable is Punctuality. This has sense because students have to arrive on time to the lessons or exams. In this case also five terminal nodes were produced, involving different variables from the tree generated for occupation reasons. The variables used for these decision rules were the Punctuality, Safety, Temperature and Frequency.

According to Other reasons for travelling (see Table 5), also other variables were used for generating the tree, as for example the Fare, that it was not considered before,
neither the overall sample of users, nor for passengers travelling for occupation or studies purposes. In this case information becomes the most discriminant variable in the root node as happens with the tree generated with the overall sample.

These three models are 65.86%, 67.67% and 69.58% accurate, respectively, and the accuracy rate of the decision rules is high in almost all of them, with values over 55% in most part of them, and values under this rate mainly in the decision tree created for Other Reasons, in which a high heterogeneity among users’ opinions is still presented.

Another crucial outcome provided by the CART modeling is the importance of the variables in the model. It is obtained through the importance index (XXVIII). Table 6 shows the normalized importance of the variables deducted from each of the models developed.

Punctuality, Temperature, Information and Frequency are the most important attributes on SQ in the metropolitan bus transport for the overall market (Table 6). A number of authors who have analyzed SQ for bus transport, have also identified Punctuality as one of the attributes with the greatest impact on overall SQ (XXVI, XVIII), as well as Temperature and Frequency, that were also identified as having a lot of weight on SQ by dell’Olio et al. (XXVI).

By considering the most important variables at each market segment, they show significant differences. For example, for people travelling for occupation, the most important variable was the Frequency, followed by the Information, Punctuality and Space. In the case of people travelling for Studies, the most important variable was the Punctuality, and not the Frequency as happened with the group of users before.

For students the Temperature, Space and Safety are also some of the most important variables. Finally, for people travelling for other reasons, such as doctor, shopping, holidays, etc, the Information holds the first place in the ranking of importance. This differences between market segments demonstrate that it is very important to analyzed these groups of passengers separately, in order to discover their needs and preferences towards the service, for carrying out a personalized marketing more appropriate for each of them.

### Conclusions

The massive use of the private vehicles in the cities and the necessity of generate a more sustainable mobility in the cities and their metropolitan areas has forced public transport administrations to look for different solutions to this situation. One of these solutions is to promote the use of public transport modes by increasing the level of quality of them.

For achieving this purpose, we have proposed decision trees methodology as an interesting approach for transport planners for evaluating service quality and for extracting useful and powerful information of its results that helps them to formulate more successful strategies.

With this methodology, the quality of the metropolitan public bus transport of the city of Granada (Spain) was analyzed, and the variables that had a notable impact on service quality were identified. Moreover, in order to diminish the heterogeneity presents in passengers opinions, three different segments of passengers were studied, according to their reason of travelling: Occupation, Studies or Others.

CART models provided good predictions in the four decision trees built, with accuracy values above 65.86%.
Also the accuracy rates of the decision rules extracted from the trees were high, being higher than 55% in almost all of them.

Some differences were identified between the overall market and the market segments most important variables. While for the overall market and the passengers that take the bus for studies purposes, the most important characteristic of the service was the Punctuality, for the people that travels for reaching work their most influent variable was the Frequency. If passengers travel because of other reasons, they are most focused on the Information. This demonstrates that such segmentations can lead to sample homogeneity.

Therefore, policies for improving service quality in public transportation can only succeed if specific measures direct to specific groups of passengers are developed. A generic framework of action is not recommended.

**Acknowledgements**

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Table 6. Normalized derived importance rates.


XXV. De Oña and de Oña (2013). Analyzing transit service quality evolution using decision trees and gender segmentation. WIT Transactions on the Built Environment 130, 611-621


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