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Investigating the traffic-related environmental impacts of hydraulic-fracturing (fracking) operations

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ABSTRACT

Hydraulic fracturing (fracking) has been used extensively in the US and Canada since the 1950s and offers the potential for significant new sources of oil and gas supply. Numerous other countries around the world (including the UK, Germany, China, South Africa, Australia and Argentina) are now giving serious consideration to sanctioning the technique to provide additional security over the future supply of domestic energy. However, relatively high population densities in many countries and the potential negative environmental impacts that may be associated with fracking operations has stimulated controversy and significant public debate regarding if and where fracking should be permitted. Road traffic generated by fracking operations is one possible source of environmental impact whose significance has, until now, been largely neglected in the available literature. This paper therefore presents a scoping-level environmental assessment for individual and groups of fracking sites using a newly-created Traffic Impacts Model (TIM). The model produces estimates of the traffic-related impacts of fracking on greenhouse gas emissions, local air quality emissions, noise and road pavement wear, using a range of hypothetical fracking scenarios to quantify changes in impacts against baseline levels.

Results suggest that the local impacts of a single well pad may be short duration but large magnitude. That is, whilst single digit percentile increases in emissions of CO_2, NO_x and PM are estimated for the period from start of construction to pad completion (potentially several months or years), excess emissions of NO_x on individual days of peak activity can reach 30% over baseline. Likewise, excess noise emissions appear negligible (<1 dBA) when normalised over the completion period, but may be considerable (+3.4 dBA) in particular hours, especially in night-time periods. Larger, regional scale modelling of pad development scenarios over a multi-decade time horizon give modest CO_2 emissions that vary between 2.5 and 160.4 kT, dependent on the number of wells, and individual well fracking water and flowback waste requirements. The TIM model is designed to be adaptable to any geographic area where the required input data are available (such as fleet characteristics, road type and quality), and we suggest could be deployed as a tool to help reach more informed decisions regarding where and how fracking might take place taking into account the likely scale of traffic-related environmental impacts.

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1. Introduction

1.1. Aim of the paper

The exploration and potential production of oil and gas from shale reservoirs using hydraulic fracturing (fracking) technology has raised significant public concerns about a range of possible environmental impacts as diverse as the potential for fracking to cause earthquakes (e.g. Davies et al., 2013) to the contamination of water supplies (Osborn et al., 2011; Davies et al., 2014). The environmental impacts of road traffic associated with drilling and fracking operations has been an additional concern (King, 2012), but there are few analyses of these potential impacts in the peer-reviewed literature.

Fracking an exploration or production well requires additional, primarily Heavy Duty Vehicle (HDV) traffic associated with the use and disposal of water and chemicals used in the fracking process. Since gas resource estimates, for example in the UK and across Europe, are significant (DECC, 2010; Andrews, 2013) and there is an active debate around the environmental risks, assessment of the impact of road traffic is both timely and important.

The aim of this paper is therefore to produce a scoping-level environmental assessment for the short-term local impact of an individual site, as well as a longer-term assessment of the temporal impact of a number of sites operating in a particular region, over a timeframe of several decades, using a newly-created Traffic Impacts Model (TIM). This should help inform the current debate around the impact of increased traffic associated with the deployment of this technology, specifically

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for the UK (on which our hypothetical modelling scenarios are based) and the rest of Europe, but with relevance to other countries where fracking is active, such as the US and Canada, or being considered (e.g. Australia, China and South Africa).

1.2. Well drilling and fracking

The drilling of a well requires the building of a well pad, movement of a rig and related equipment and materials to the site, for example casing, cement and the chemicals required to make up drilling mud. The fracking process is undertaken after the well has been drilled. Rather than one fracking operation, fracking is normally carried out along different sections of a horizontal or vertical well in what is called a multi-stage fracking operation. Total volumes of water used per well vary considerably, from 1500 m^3 to 45,000 m^3 (e.g. King, 2012). The process requires water to be pumped down the well along with chemicals and proppant (usually ceramics or sand). After pumping has finished, the fracking fluid (including natural contaminants) returns to the surface. As with initial water demand, flowback volumes are variable. In US operations the volumes returning can be 5–50% of the injected volume (King, 2012). Over a period of a few days to a few weeks flowback decreases and gas production commences. A production well pad could include 12 or more wells, which may be re-fracked several times, once production has declined. It subsequently becomes necessary to remove flowback water from those sites both during and after fracturing. If this transportation is done by road, as has typically been the case in the US and Canada, then considerable volumes of HDV (i.e. tanker) traffic may be generated, albeit for relatively short periods (i.e. weeks) of time.

1.3. Traffic impacts

HDVs cause visible disruption and traffic congestion, especially if routed along roads that may be considered inappropriate, such as those carrying light traffic in rural areas, or at inappropriate times of the day. Vehicle movements are associated with production of greenhouse gas (GHG) emissions, primarily in the form of Carbon Dioxide (CO_2). The production of CO_2 from traffic emissions due to shale gas exploitation has been previously examined by Broderick et al. (2011), with on-road emissions estimated at 38 t–59 t CO_2 per well. Broderick et al. (2011) also suggested that total CO_2 emissions associated with extraction of shale gas from a well were small (0.2–2.9%) compared to total emissions from combustion of the gas produced by the well.

HDVs are associated with disproportionate annoyance arising from noise emissions when compared to lighter vehicles (Sandberg, 2001), and their diesel engines are perceived as 'dirty' in terms of local air quality emissions of Oxides of Nitrogen (NO_x) and particulate matter (PM), even though modern vehicles are fitted with a variety of exhaust treatment devices to meet emissions standards (the 'Euro' standards) in effect across the European Union, and adopted globally in other countries, such as China and Australia. At the time of writing, the EURO VI standard (Reg (EC) No. 595/2009) is the highest in effect for HDVs (OJEC, 2009).

Emissions of gases affecting local air quality may have been historically of less importance in the US and Canada, with much drilling taking place away from urban areas. However, this may not be the case in more densely populated areas such as in Europe, where exploration may occur relatively close (i.e. within kilometres) to sub-urban locations resulting in HDVs travelling through inhabited areas. Historically, large urban areas, and areas adjacent to major highways, especially in the UK, have had problems meeting statutory limits on concentrations of Nitrogen Dioxide (NO_2 — a component of NO_x) and PM_{10} (particulate matter with aerodynamic size under 10 μm).

Aside from physical emissions of gases and noise, concern has also been voiced about the damage caused to pavement surfaces and the underlying road structure through additional loading by HDVs. Such vehicles cause a disproportionate amount of loading when compared to lighter vehicles, and may substantially shorten the lifespan and increase deterioration of roads not designed with their presence in mind.

Other traffic-related issues that have been raised in the debate about fracking and require rigorous research are: potential increases in the number of accidents (involving direct injury and damage to property, or accidental spillage of materials or chemicals), issues with vibration, community severance, delay (to pedestrians and other drivers) and disruption of normal activity patterns, increases in traffic violations, which all feed into marginal economic effects where the cost of operation of a site may be borne by the local community, rather than the site operator, if appropriate policy mechanisms to redress imbalances are not provided.

1.4. Traffic volume and intensity

Estimation of the potential volume of traffic generated by shale gas exploitation associated with a particular drilling site, or over a given region, is compounded by a number of factors. Aside from uncertainty over total quantities and precise locations of resources to be exploited, a number of other issues and considerations may be highlighted.

First, modern techniques allow for multiple wells to be operated from a single well pad during full production. NYS DEC (2011) reports that 90% of Marcellus Shale development (Pennsylvania, US) is expected to be by 'horizontal wells on multi-well pads'. Examination of literature, online resources and anecdotal evidence suggests 6-, 8-, 10- or 12-well pads are now standard operating practice in the US (DEC, 2008; SEAB, 2011; DrillingInfo, 2014).

Second, there is a large amount of variability reported in the amount of water and proppants required at each well, which depends on the underlying geology, and the number of potential stages of fracking. The single well to date in the UK at Preese Hall (Lancashire) required 8400 m^3 of water (Cuadrilla, 2014a). A summary of US literature, produced for the European Parliament (EP DGIP, 2011) suggests volumes per well (including initial drilling) in the range of 1500 to 45,000 m^3. Jiang et al. (2013) reported using a normal distribution with mean 15,000 m^3 and overall range from 3500 to 26,000 m^3 to model demand for the Marcellus Shale deposits. Broderick et al. (2011) suggest that each stage of a fracking operation for a single well will require between 1100 and 2200 m^3 of water, leading to a total demand of 9000 to 29000 m^3 per well, or 54,000 to 174,000 m^3 for a six-well pad. If a base requirement of 20,000 m^3 of water and 5% by volume proppant is assumed, this equates to a transportation need for delivery of 1000 m^3 of sand, or 1700 t of sand (assuming dry sand with density 1700 kg/m^3), though fracturing additive requirements in some countries may be lower than typical US values, based on exploratory data (Broderick et al., 2011).

Third, there is large variability reported in the amount of flowback material produced. The US Environmental Protection Agency (US EPA, 2010) suggests that the rate recovery of injected fluids from hydraulic fracturing is variable — ranging between 15 and 80%. NYC DEP (2009) suggests use of a 'worst case' option of 100% for the calculation of tanker demand, whilst NYS DEC (2011) reports 9% to 35% returned water for Marcellus Shale wells in Pennsylvania, and Cuadrilla report values of 20 to 40% (Cuadrilla, 2014b). For modelling purposes Broderick et al. (2011) assumed 50%.

Fourth, during the operational lifetime of the well, which may be a period of 5 to 20 years, there may be the need for further stimulation via periodic re-fracturing (or re-fracking). Each re-fracturing event may entail similar, if not higher, water and waste demands to the initial process (Sumi, 2008). Broderick et al. (2011) assumed a single re-fracturing of 50% of wells for UK-wide shale gas scenarios.

Finally, aside from the actual fracking and waste disposal transport demands, there will also be vehicle movements associated with: construction of access roads and site facilities, excavation and concrete pouring for the pad, transportation of drilling equipment, well casings, water tanks and pump equipment to site, excavation equipment used

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to dig waste pits, completion and capping material transport, and general movement of workers to and from a site.

However, the vast majority of movements (typically 70% or greater) are associated with the fracking and flowback processes. Table 1 presents data from NYC DEP (2009), cited by Broderick et al. (2011), illustrating total truck movements associated with a fracking operation requiring between approximately 12,500 m^3 (low) and 18,750 m^3 (high) of water and proppants per well, with approximately 50% flowback of fluid waste.

Re-fracturing activities could add a further 2000–3000 HDV trips to the estimates in Table 1 (Broderick et al., 2011). Limited tanker movements (2–3 per well per annum) to remove produced water during the operational lifetime of a well may also be necessary (NYS DEC, 2011).

The duration of activities at a site also determines the intensity of demand for transportation over a given period. NYC DEP (2009) suggests that total operations for the six well pad outlined in Table 1 would span between 500 and 1500 days. However, the peak of HDV demands occur in the delivery of water and proppant between 30–60 days prior to commencement of fracking, with flowback fluid return occurring for 42–56 days after. Transport demands may be complicated by the overlapping of phases between individual wells on a pad (e.g. water deliveries occurring during horizontal drilling), or by operation of multiple well activities in parallel (though actual drilling of more than two wells simultaneously is considered unlikely). Demand intensity may also be mitigated by the provision of water storage facilities and lined waste pits on-site, acting as buffers to demand.

It cannot be ruled out that water transportation to the well pad during exploration, development or after production has commenced could be via pipeline, as was the case for the UK's first fracked shale exploration well at Preese Hall, Lancashire (Mair, 2012).

2. Methods

2.1. The model

A Traffic Impacts Model (TIM) has been developed to produce a broad, scoping-level environmental assessment for a small number of well pads operating in a region, over a timeframe of several years. As outlined in the introduction, the primary input drivers of the model are the water and proppant demands of fracking at well pads, whilst the primary outputs are local air quality, GHG and noise emissions, plus estimates of axle loadings in the region.

The TIM consists of four main components:

1. a traffic demand model, which utilises information about the scale and duration of activities in a region where fracking is being undertaken, in order to produce the pattern of traffic associated with those activities;
2. a traffic assignment model, which uses the traffic demand data to calculate temporal and spatial patterns in vehicle flow and speeds on the roads being used to supply the region;
3. an environmental model, which uses the patterns of assigned traffic to calculate impacts for a number of assessment criteria; and
4. a post-processing module that collates and statistically summarises information, to compare the impact of operations with regards to the baseline traffic.

Each component is discussed in more detail in the following sections. The traffic demand, assignment and post-processing components are novel in this work, whilst the environmental model forms part of the pre-existing PITHEM (Platform for Integrated Traffic, Health and Environmental Modelling) tool (Namdeo and Goodman, 2012).

Table 1
Truck visits over the lifetime of a six-well pad.
Source: Broderick et al. (2011), based on NYC DEP (2009).

Purpose	Per well		Per pad	
	Low	High	Low	High
Drill pad and road construction			10	45
Drilling rig			30	30
Drill fluid and materials	25	50	150	300
Drilling equipment (casing, drill pipe etc.)	25	50	150	300
Rig completion			15	15
Completion fluid and materials	10	20	60	120
Completion equipment (pipes, wellheads)	5	5	30	30
Hydraulic fracture equipment (pumps and tanks)			150	200
Hydraulic fracture water	400	600	2400	3600
Hydraulic fracture sand proppant	20	25	120	150
Flowback water removal	200	300	1200	1800
Total (parentheses in the 'Per well' column includes additional truck visits associated with pad construction)	685 (890)	1050 (1340)	4315	6590
…of which associated directly with fracturing and flowback processes			3870 90%	5750 87%

2.2. Traffic demand

The purpose of the traffic demand model is to calculate the temporal pattern of vehicles within the study region associated with fracking activities. The model is implemented using a hierarchical series of C++ programming language classes that reflect real-world components (both physical and procedural) in a fracking operation. Class names are initially shown in single quotes ('…') in the following text.

At the top of the hierarchy is the 'region' class, which represents in abstract form an area of a country being studied. The region contains a number of 'well pads' where fracking activities take place. Each well pad may contain a number of 'wells'. Activities at the well pads and wells, outlined below, drive the generation of traffic demand. Additionally, a region contains a transport 'network', comprised of road 'links' that carry both baseline (i.e. without fracking) and fracking 'traffic'. The amalgamation of fracking demand, plus the baseline activity, give the overall level of spatiotemporal demand. The physical and spatial concepts in the TIM model are shown in Fig. 1.

As experience with fracking operations has developed, the number of possible wells per pad has increased (Section 1.4). At present the upper limit in the model is set to twelve wells per pad, though this is adjustable. It is presently assumed that pads in a given region are spaced at approximately 1.5 km distant, with a 15 km × 15 km (225 km^2) region therefore having around 100 well pads, though not all would be active at any given time (AEA, 2012).

Both well pads and wells are associated with a number of 'phases' of operation. Each phase possesses a number of attributes and classes:

1. a defined start and end time;
2. the total volume of materials needing to be serviced over the duration of the phase. Note that this volume may be either an input requirement to the phase (e.g. required building materials), or a waste product produced by the phase (e.g. flowback water);
3. links to other phases where required, defined by the volume of materials passed to subsequent phases;
4. a list of 'vehicles' that may be used to service the needs of the phase; and
5. the 'routes' used by the vehicles to and from the well pad.

In the default TIM model, the well pad has two key phases defined:

1. commissioning and construction — encompassing initial survey requirements, the development of access roads to the pad location, pad ground- and earthworks, pad concrete pouring, set-up of shared drilling equipment for wells, excavation of shared waste pits used by wells and delivery of ancillary and site equipment (e.g. site offices); and
2. decommissioning and landscaping — representing the removal of equipment from site and making good via any required landscaping

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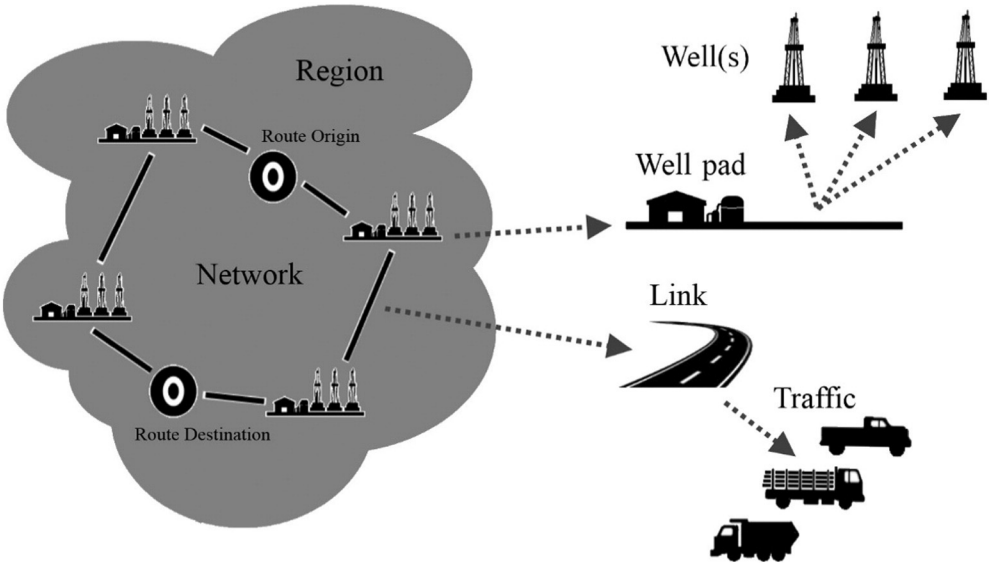

Fig. 1. Physical and spatial concepts in the TIM.

at the end of the pad's operational lifespan. The decommissioning phase may be linked to the commissioning phase so that a certain volume of materials used in construction need to be removed from site.

For each well the following phases are assumed:

1. construction and drilling — representing the arrival of drilling equipment, drill casings and drilling water at the well pad, and the removal of bored material and drilling water from site;
2. hydraulic fracturing — encompassing the delivery of water, proppant materials and chemicals to the well;
3. flowback treatment — representing the removal of waste water from the well. The flowback phase is linked directly to the fracturing phase, so that a certain percentage of waste water needs to be removed from the well; and
4. miscellaneous — encompassing all other operations and activities associated with the well, such as routine movements of site staff.

Phases themselves may overlap in time, both between individual well pads and wells, as well as internally, between activities at a specific pad or well. For example, hydraulic fracturing may be taking place at one well, whilst another well is being drilled, and flowback water is being removed from a third. Likewise flowback water removal may begin whilst a well is still in the process of being fractured. Default durations of phases have been derived from Broderick et al. (2011).

The vehicle class contains information on utilisation rate and capacity, which are used to determine the overall number of vehicles required by the phase. The vehicle class also contains the description of the vehicle, required by the environmental model (Section 2.4), and the passenger-car unit (PCU) scaling factor required by the traffic assignment model (Section 2.3). The vehicle class also contains flow 'profile' information. The profile determines when vehicles servicing the phase are considered active on the road network, and holds data for each day of the week and hour of the day. As an example, a profile may be used to apply all traffic for the phase outside of peak traffic hours, as a form of traffic management policy. Finally, the route class defines a simple static list of network links that vehicles associated with a profile will use to service the site. Fig. 2 summarises the phases and classes associated with activities at a well pad.

When run, the traffic demand model produces a temporally-ordered series of time-sliced profiles linked to their parent vehicle classes and route information for its parent region.

Whilst the initial, six phase model (two phases for the well pad and four for the well) is considered an abstract, 'high-level' model, it is considered sufficiently representative of pad activities. Further disaggregate phases, in order to model at a higher level of detail (e.g. for separate treatment of input water from one location, proppant from another, chemicals from a third etc.), or to incorporate additional technological scenarios (e.g. water is brought to the pad site via pipeline, but waste-water is still removed by tanker) are possible.

Re-fracturing of wells (Section 1.4) in order to extend their operational gas production is not explicitly covered, though may feasibly be modelled through the combination of individual runs at differing epochs, using appropriate assumptions for demand and flowback.

2.3. Traffic assignment

The traffic assignment model combines information on the baseline status of a transport network in a region, with the temporal profiles, plus vehicle and routing information, output from the traffic demand model, to produce vehicle kilometres travelled (VKT) and average speed information for individual roads, which forms input to the environmental model.

The 'network' class contains a collection of 'links'. Each link contains an identifying name, the type and length of the road, and baseline 'traffic' information. This baseline traffic information consists of a total Annual Average Daily Total (AADT) flow in vehicles per day, coupled with a diurnal 'profile', which is applied to the AADT flow to give hourly variation throughout a week. Open information from the UK Department for Transport (DfT) 'Road Traffic Statistics' datasets (DfT, 2013) was used to produce the baseline diurnal profiles for our hypothetical scenarios. Each type of road has an associated 'speed-flow' curve, which alters the calculated speed on the link, based on the flow in each hour. The road type and calculation year, are used to give the traffic fleet composition on the link. Fleet composition tables are inherited from the data in the parent PITHEM model, and are discussed further in Section 2.4.

Appropriate capacity values for the speed-flow curves are defined for types of link, with reference to UK Design Manual for Roads and Bridges (DMRB) guidelines (Highways Agency, 1999; Highways Agency, 2002). At present there are parameter values for 30 road types defined in the model, broadly covering categories of rural, sub-urban, central-urban and town and village roads. It is recognised that speed-flow curves are an abstract representation of the real-world behaviour of

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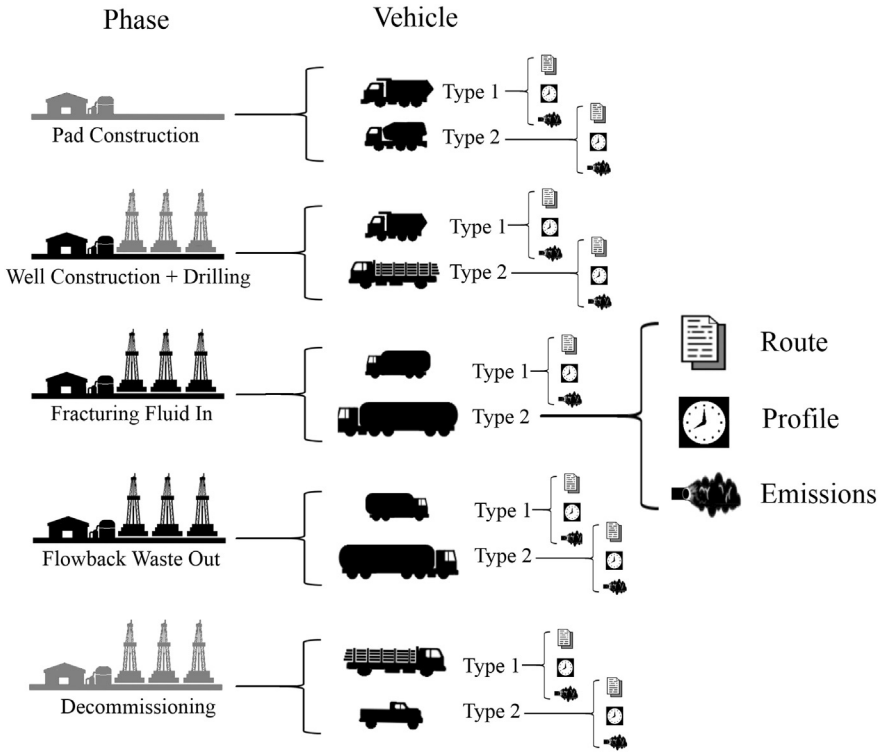

Fig. 2. Temporal phases and objects associated with well pad activities.

traffic. A congested situation will be represented as a high-flow, low-average-speed situation, rather than a more realistic low-flow, static or slow-moving queue of vehicles. This has potential implications for the accurate modelling of emissions in congested conditions in that emissions may be under-estimated. Additionally, the parameters for rural links exclude the effects of delay at junctions, which should be separately modelled (Highways Agency, 2002), but are not represented in the current approach.

2.4. Environmental assessment

2.4.1. Assessment criteria and fleet composition

As mentioned in Section 2.1, the PITHEM software (Namdeo and Goodman, 2012) has been used to provide the assessment of key environmental criteria based on the output from the traffic assignment model. The environmental criteria used are split into four broad categories:

1. greenhouse gas emissions (tailpipe 'ultimate CO_2' or 'uCO_2' emissions);
2. local air quality emissions (tailpipe NO_x, HC and primary NO_2 emissions, PM_{10}, $PM_{2.5}$ including brake and tyre wear components);
3. noise level at the roadside; and
4. standardised axle loading applied to the road.

Calculation of all of the above criteria depends on appropriate vehicle characteristics, combined with tabulated fleet composition information, to produce correctly weighted additions of contributions from both the vehicles used to describe fracking traffic demand and from the baseline fleet. For our demonstration scenarios in Sections 3.2–3.3, fleet data are taken from the UK National Atmospheric Emissions Inventory (NAEI, 2011), supplemented with data from the Emissions Factor Toolkit (EFT), Version 5.1.3 (DEFRA, 2012). These data provide a description of current and projected vehicle types (broken down by chassis type, weight, fuel, engine size and emissions control technology) for a range of years from 2008 to 2035. Separate fleet descriptions are given for broad categories of road: urban roads, rural roads and motorways.

Within the fleet composition tables, there exist temporally evolving splits of Euro emission control measures, driven by underlying vehicle uptake, renewal and scrappage assumptions. Sample 'Euro class' splits for rigid and articulated heavy goods vehicles for the years 2010, 2015 and 2020, from EFTv5.1.3 are given in Table 2 below.

As can be seen from Table 2, in 2010 the majority of goods vehicles were assumed to fall within the EURO III and IV emissions control categories, whilst by 2015 the EURO V and VI categories form the largest segments. At 2020 (and beyond) the majority of goods vehicles fall into the cleanest EURO VI control category. Regarding the weight and capacity of vehicles, it has been assumed that a 40 t laden-weight articulated tanker has a capacity of 30,000 l (30 m^3) of water, whilst a 26 t laden-weight rigid body tanker has a capacity of 15,000 l (15 m^3). Further assumptions on the weights and capacities of other vehicles are required for each operational phase. These have primarily been taken from analysis of data in NYS DEC (2011), supplemented with information from the transport section Environmental Statement made for the potential Roseacre Wood, UK site (ARUP, 2014).

Table 2
Example percentage splits of emissions control technologies (EURO classes) for rigid and articulated HGVs in select years.

Technology	2010		2015		2020	
	Rigid	Artic	Rigid	Artic	Rigid	Artic
Pre-EURO	–	–	–	–	–	–
EURO I	0.49	0.06	–	–	–	–
EURO II	10.41	2.69	0.74	0.07	–	–
EURO III	41.42	30.69	13.74	3.07	0.71	0.06
EURO IV	25.82	31.57	12.58	6.01	2.78	0.33
EURO V (EGR)	5.46	8.75	9.65	10.51	3.08	1.29
EURO V (SCR)	16.39	26.25	28.94	31.52	9.25	3.87
EURO VI	–	–	34.36	48.83	84.18	94.44

NB: Figures may not add up to 100% due to rounding. EGR = Exhaust Gas Recirculation technology, SCR = Selective Catalytic Reduction technology. Both EGR and SCR are 'de-NOx' technologies, see Section 2.4.3.

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2.4.2. Greenhouse gas emissions

Greenhouse gas (GHG) emissions are represented by ultimate CO_2 emissions (total mass of CO_2 after all exhaust components of fuel exhaust have oxidised). The calculation of uCO_2 is based on the speed-emissions curves presented in Boulter et al. (2009), which also form part of the UK Emissions Factor Toolkit, Version 5.1.3c.

The emissions function forms a 'U-shaped' curve, considered valid over a type-specific speed range (typically 5–120 km/h for light vehicles and 10–90 km/h for heavy vehicles). Outside of these ranges, values are clamped to prevent excessive emissions rates. Total emissions for a link are calculated from the summation of individual contributions for all fracking traffic types active in the period, for comparison to the baseline fleet contribution.

2.4.3. Local air quality emissions

Emissions for those pollutants considered detrimental to local air quality (LAQ) are calculated using the same methodology for uCO_2, outlined above, with additional fuel quality and vehicle mileage scaling correction factors from the EFT applied (DEFRA, 2012) after calculation of the base emissions rate. For particulate matter and hydrocarbons, the emissions functions have the same form as that for uCO_2 above, with co-efficients from Boulter et al. (2009). For NO_x a variety of functions are used, based on those found in the COPERT4 (COmputer Program for Emissions from Road Transport) version 8.1 methodology (EEA, 2007; NAEI, 2012).

In accordance with the EFT, particulate matter emission rates (PM_{10} and $PM_{2.5}$) are scaled from an initial tailpipe emissions calculation, plus contributions from brake and tyre wear and re-suspended particles. Primary emissions of NO_2 (i.e. those emissions of NO_2 directly from the vehicle tailpipe, prior to the additional generation of NO_2 from photochemistry) are calculated based on the initial NO_x emission, with the percentage conversion factors presented in Boulter et al. (2009) applied.

At present, both the GHG and LAQ emissions functions assume that heavy vehicles are 56% laden over a round trip, based on UK DfT freight transport statistics (DfT, 2013), which is considered equivalent to a tanker arriving on site full, then departing almost empty. Ideally, separate emissions rates would be calculated for each journey leg. The same limitation exists in the standard EFT (DEFRA, 2012) emissions factors.

2.4.4. Noise

Roadside noise levels are calculated using a methodology derived from the CNOSSOS-EU (Common Noise assessment methods in Europe) procedure (Kephalopoulos et al., 2012), developed to fulfil the mapping requirements of the European Noise Directive (OJEC, 2002). The CNOSSOS-EU methodology predicts octave-band noise emissions for five vehicle classes (light vehicles, vans, heavy vehicles, powered two wheelers (PTW) and other), based on separate emissions functions for rolling noise and power-train noise.

Noise emissions are described in terms of an energy-averaged sound power level. Sound power levels are difficult to interpret, as they cannot be readily compared to conventional predictions of noise based on sound pressure levels. Hence, a further conversion to an equivalent roadside noise level (L_{Aeq} level) at 10 m from the road is applied, based on a number of propagation assumptions. This conversion methodology is outlined in Watts et al. (2004).

2.4.5. Axle loading

The final component of the environmental assessment is the calculation of axle loading over the period of fracking operations. Axle loading is assumed to be a proxy for damage to both the road surface and underlying structure caused by traffic (Highways Agency, 2006) and is presented in units of 'Equivalent Standard Axle Loads' (ESAL) for a road over a period of time. This calculation is based on the well-established 'fourth-power law' (ratio of axle load to standard 80 kN load, raised to the fourth power, AASHTO, 1986).

This calculation represents a crude measure of loading damage, which may only be applicable for permanent or semi-permanent flexible (i.e. asphalt) or rigid (i.e. concrete) pavements. Estimation of damage to unsealed, temporary roads or tracks (i.e. construction access roads, farm tracks) is problematic, given the dependency on specific site soil, drainage and weather conditions. Unlike the Highways Agency's DMRB methodology (Highways Agency, 2006), the calculation also includes contributions from light vehicles and vans.

2.4.6. Post-processing

The post-processing procedure collates the individual, period-based pollutant results and calculates absolute and percentage changes in each parameter. The time horizon considered for the calculation of overall impacts in comparison to the baseline may be based on one of three approaches:

1. calculation of the baseline over the overall total duration of fracking activities in all phases across the region, i.e. the time from the start of construction of the first well pad in the region, to decommissioning of the last well pad in the region (i.e. including the operational, gas-producing, lifetimes of the well pads);
2. calculation of the baseline over the activities from the start of construction of the first well pad, to the end of hydraulic fracturing activities (coinciding with the assumed start of operational gas production) at the last well pad; and
3. direct comparison, with the equivalent baseline results only calculated over those periods when any phase activity is occurring in the region.

Adopting the first approach could result in a time horizon of 20+ years, whilst the second or third may give a time horizon of 1–5 years. Comparisons of emissions over a longer baseline reduce the percentage increases reported by the post-processor.

3. Results

3.1. Scenario testing

This section presents results from the TIM in relation to short-term temporal outputs for a single well pad. This is followed by subsequent analysis using the assumptions made for that well pad, applied to multiple well pads in a region, over an extended time horizon.

3.2. Impacts of a single well pad

TIM output for a single well pad has been compared to the analysis performed in Broderick et al. (2011). That analysis considered traffic-related uCO_2 emissions from a six-well pad. The assessment has been expanded here to include the additional environmental outputs available from the TIM model.

The analysis uses the 'low' and 'high' water and proppant demands, flowback percentages and ancillary vehicle demands given in Table 1 — summarised as 685 HDV movements per well in the 'low-water use' scenario estimate, and 1050 HDV movements per well in the 'high-water use' scenario estimate. As per Broderick et al. (2011) vehicle routes form a 60 km round trip. Operations at the well pad are assumed to take 85 weeks to complete. The TIM model was run for three initial years, 2010 (as per Broderick et al., 2011), 2015 and 2020, using the vehicle technology assumptions from Table 2. The TIM was run applying vehicle demand to four different road types: a rural village road (baseline flow of 2000 veh/day speed limit 30 mph, 48 km/h); a good quality suburban road (8 veh/day, 40 mph, 64 km/h); a good quality rural road (2500 veh/day, 50 mph, 80 km/h) and a motorway (40,000 veh/day, 70 mph, 113 km/h). Hence, for each entry the range of emissions per well from the four road types is presented. Air pollutants are expressed as mass of additional emission over baseline emissions/well, noise as the increase in roadside L_{Aeq} levels in dB, averaged over the period,

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whilst ESAL is given as the additional standard axle loading (thousands of axles) per well throughout the period.

At 35 to 59 t per well, the CO_2 emission rates from the TIM model for a start year of 2010 are in line with those reported by Broderick et al. (2011). This is to be expected given that both models share a common source of data in the DEFRA Emissions Factor Toolkit (DEFRA, 2012). Even though Broderick et al. (2011) used a previous version of the EFT, CO_2 emissions factors have remained constant through a number of successive EFT versions. It is also notable that CO_2 emissions factors for the HDV segment show little change across the three periods considered, as it is assumed in this instance that fuel consumption savings through advancements in vehicle technology are counteracted by increased fuel requirements caused by exhaust treatment systems (particle filters, de-NO_x catalysts etc.) in later vehicles. The CO_2 emissions are also relatively invariant with speed, when compared to the LAQ pollutants.

The results for the individual pollutants show large changes with both road type (primarily due to the underlying speed assumptions) and base year selection, though the key driver of emissions reductions with time is the increasing presence of EURO VI vehicles within the fleet composition. Indeed, fleet and technology changes over the decade are predicted to decrease HDV NO_x emissions by around 90%. Progress in reductions of particle matter is substantial, but less noticeable, given that large reductions achieved through the introduction of diesel particulate filters (DPFs) were achieved previously in earlier EURO classes.

Fig. 3 presents the effect of road type, and underlying baseline traffic assumptions on the relative increases in VKT, GHG and LAQ emissions, noise and axle loading over the 85 week period of pad operation. Given the high capacity and baseline flow, the results for the motorway show negligible (<0.5%) relative change, with the suburban, rural and village road scenarios show increasing relative change over the decreasing baseline flow.

In all cases, for all emission parameters except hydrocarbons, relative percentage increases are disproportionate compared to the additional VKT travelled, given the higher emissions from HDVs compared to light vehicles. The effect is most noticeable in terms of axle loading over the period, with a 0.9% increase in VKT in the 'village road/low-water consumption' scenario accounting for a 17% increase in the ESAL value. NO_x emissions increase by 6%, uCO_2 by 5% and emissions of other pollutants by 0.7 to 4.5%. In the 'village road/high-water consumption' scenario, a 1.1% increase in VKT leads to a 25% increase in ESAL, compared to a 0.06% increase in VKT and a 0.5% increase in ESAL for the 'motorway/high-water consumption' scenario.

In addition to the comparison of overall operations to baseline, the TIM model has been used to produce outputs for individual phases of operation. Figs. 4 and 5 examine diurnal-period NO_x emission rates and roadside L_{Aeq} levels for the 'village roads' scenario, at the periods of maximum predicted traffic to the pad, under a variety of different site access policies, being: 24/7 'all-day' access to the site, movements limited to 'daytime' (0600–1900), movements limited to the overnight period, movements limited to the daytime, inter-peak traffic period (1000–1600) and movements restricted to peak traffic hours (0700–1000, 1600–1900). The maximum predicted traffic occurs assuming that two wells are in operation on the pad simultaneously, one undergoing final water and proppant deliveries in the week before initial fracturing, whilst the second is undergoing initial drilling. In the low and high scenarios this situation equates to 71 or 109 vehicle movements to and from site per day. In the 600 day lifecycle to completion of the pad, this situation is assumed to occur three times.

Total daily NO_x emissions increase by 18%–20% (low scenario), and 27%–30% (high scenario) depending on access policy. In both scenario runs the best policy for diurnal total emissions is overnight access, which creates negligible conflict with baseline traffic, though the relative emissions in the overnight period increase by a factor of 2–2.6. The worst policies for diurnal total emissions are, predictably, allowing access only in peak hours, or during the inter-peak periods, where baseline traffic flows are high, though relative increases are lower, by a factor of 1.4–1.8.

Conversely, the overnight policy is viewed as very detrimental to noise levels, with 2.5 to 3.4 dBA increases predicted to the hourly L_{Aeq} values, effectively doubling the sound pressure at roadside, and being clearly perceptible, even discounting effects to sleep disturbance, due to peak events (L_{Amax} levels) associated with HDV passbys (WHO, 2009). Increases in relation to the peak- or inter-peak policies are more marginal at 1.1–1.8 dBA.

The noise results highlight an issue with the calculation of long-term average L_{Aeq} values, as would be required for noise mapping activities compliant with the European Noise Directive (OJEC, 2002). The actual contribution of fracking operations normalised over the period of operations may be considered miniscule, with increases of under 1 dBA being generally un-perceptible as a change to humans, and well within the expected range of uncertainty in such modelling. However, this interpretation ignores the fact that the change in noise level due to a particular phase of operation may be far greater (see Fig. 5), and people's perception of the whole period may be skewed by such events. Nor does it consider that subjective annoyance to noise may be further exaggerated by frequent peak-events, substantive increases in levels over previously very quiet background levels and noise in evening or night periods. All of these issues are not adequately represented by a single L_{Aeq} value.

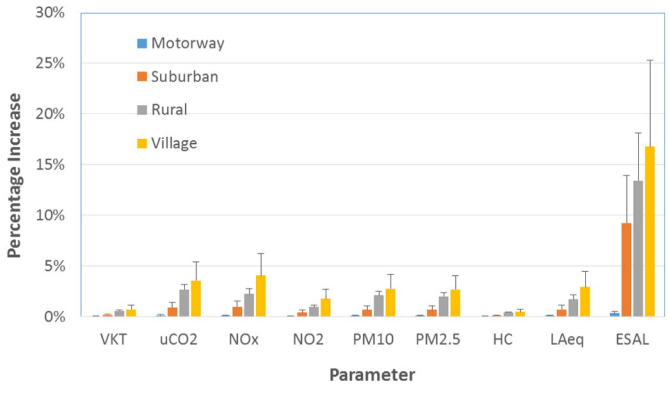

Fig. 3. Percentage increases over baseline values for vehicle kilometres travelled, GHG and LAQ pollutants, noise and axle loading, assuming six-well pad operation using differing road types. Vertical bars show the difference between the 'low-water use' and 'high-water use' scenarios.

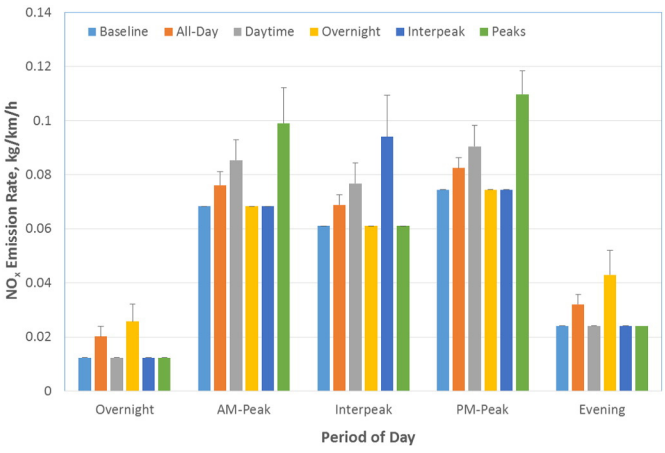

Fig. 4. Peak operational NO_x emission rates compared to the baseline profile under differing vehicle arrival and departure policies.

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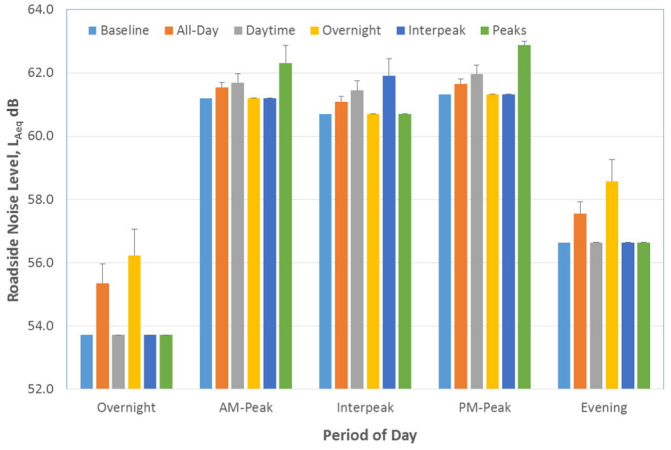

Fig. 5. Peak roadside L_{Aeq} noise levels compared to the baseline noise levels under differing vehicle arrival and departure policies.

3.3. Region and UK wide scenarios

In addition to the localised impacts studied above, a number of larger scenarios have been simulated to explore the magnitude and temporal profile of emissions (CO_2, NO_x and PM_{10}) regarding the development of a region, over a number of years. Four initial development scenarios were assumed: low (190 wells), medium (400 wells) high (810 wells) and ultra (2970 wells). The first three well number assumptions were taken from Regeneris (2011), regarding potential exploitation of Bowland Shale resources in Lancashire, UK, the 'ultra' value being taken from the estimated total calculated by Broderick et al. (2011) to meet 10% of UK annual gas consumption (2010 baseline) over a 20 year period.

Four well development timelines were considered over the 2015 to 2050 horizon, to give 16 baseline scenarios:

- an assumed normal distribution of wells developed per year ($\mu = 2025$, $\sigma = 3$ years);
- an 'early' development timeline (Norm dist. $\mu = 2018$, $\sigma = 3$ years, skew $= -3$);
- a 'late' development timeline (Norm dist. $\mu = 2032$, $\sigma = 3$ years, skew $= +3$); and
- uniform development over the years 2015 to 2035.

Under these assumptions the timelines based on the normal distributions peak at 25 (Low) to 395 (ultra) wells being developed in a single year, whilst the uniform timeline provides between 9.5 (low) and 150 (ultra) wells per year.

Each of the baseline scenarios was subsequently further tested with two additional assumptions:

- in order to sustain production, 50% of the wells coming on-stream in a given year would be re-fracked five years later; and
- that 90% of fracking water demand could be met by pipeline, with flowback and produced water removed by tanker.

The same assumptions for the localised low-water demand well analysis outlined in Section 3.2 were applied for each well pad. Finally, all scenario combinations were tested using four road networks: a motorway network, a primary-rural network, a sub-urban network and a minor rural road network. Baseline traffic growth on the network over the period was assumed from the 'Scenario 2' forecast scenarios outlined in the UK National Transport Model (NTM). All combinations of the above result in a total of 256 scenario runs.

Fig. 6 presents the additional CO_2 emissions results due to fracking operations under 'early' and 'late' timelines, assuming all water demands are met solely by tanker, on the minor rural road network. Total CO_2 emissions over the 20 year period vary from 6.6 kT in the 'late low' scenario to 108 kT in the 'early ultra' scenario.

The lower total values and peaks in the late development timeline reflect the technology-based fuel consumption savings assumed for HDVs, taken from the NTM, amounting to an additional 6% reduction in each of the late adoption scenarios out to 2035.

Figs. 7 and 8 present the additional annual CO_2 and NO_x emissions associated with the low development scenario (190 wells), for all timelines, both with and without re-fracturing. Total CO_2 emissions vary between 6.6 kT and 10.3 kT, with the 'early' timeline producing the highest emissions. The need for re-fracturing adding an additional 48% to the emissions total in the 'early' and 'normal' timelines and 49% in the 'uniform' and 'late' timelines. For NO_x and PM_{10} the total ranges were 3.40–7.70 t and 0.85–1.29 t respectively, with the 'early' timeline producing 70% more emissions than the 'late' timeline, given the predominance of Euro V (and earlier) vehicle technologies in the initial fleets. The decrease in NO_x production with fleet turnover to Euro VI is especially noticeable in the 'uniform' timeline, which exhibits a rapid decay to almost constant values beyond the mid-2020s. Later adoption makes smaller absolute, but greater relative changes, to NO_x and PM_{10} emissions totals when considering the impact of re-fracturing.

Fig. 9 presents the CO_2 emission results for the 'early low development' timeline, with and without re-fracturing and with and without the assumption that 90% of initial demand for drilling and fracturing water can be met by the existing water network. All flowback and produced water are then removed from site by tanker. This reduces the total HDV VKT for a given well to just under 40% of that assuming full demand is met by tanker. Commensurate reductions occur for all pollutants, driven primarily by the VKT changes, with only minor variation potentially attributable to changes in speed with reduction in traffic.

Further to the results presented in Table 3, the choice of road network, and hence underlying base flow, traffic growth, speed and congestion assumption, made relatively little impact on total additional CO_2 estimates, but could drastically alter the estimates for PM_{10} and especially NO_x, with NO_x estimates for the predominantly motorway-based network being only 40–50% of those values shown in Fig. 8, reflecting the behaviour of the underlying emissions curve to gross changes in speed (i.e. >20 km/h) between dominant categories of road in the network.

Table 4 provides a summary of the mass of fracking water moved, total vehicle kilometres travelled and emissions associated with the minor road dominant (i.e. worst case) scenarios.

The values in Table 4 may be placed in context with regional or national data. For example, the 'ultra' scenario, assuming no re-fracturing and no water supply by pipeline, involves lifting a tonnage water over a 20 year period comparable to total production of petroleum products in the UK in a single year (~64 Mt produced in 2013, DECC, 2015; ~59 Mt lifted in 2013, DfT, 2015a). Likewise, the 'ultra' scenarios produce VKT values over a 20 year period that are comparable to 10–42% of total VKT travelled by bulk liquid transporters in the UK in 2013 (DfT, 2015b). The 'medium' scenario assuming one re-fracturing and supply of water by tanker is equivalent in tonnage to forecourt petrol deliveries to the four major UK supermarket chains in a single year (12.2 Mt in 2013, DECC, 2015). The CO_2 emissions for the 'ultra' scenarios are approximately equivalent to those from transport associated annually with a mid-sized town (e.g. CO_2 emissions from the UK market town of Burnley in Lancashire (pop. 73,000) were estimated at 131 kT in 2012, emissions from all minor roads in the county as a whole were 737 kT, and for all transport sources were 2.57 Mt, DECC, 2014). It is noted that the number of wells involved in the 'ultra' scenarios is two orders of magnitude below the currently active gas wells in the United States (~493,000 in 2009 of which 90% have been fracked, Urbina, 2011). Additionally, it should be kept in mind that Table 4 only relates

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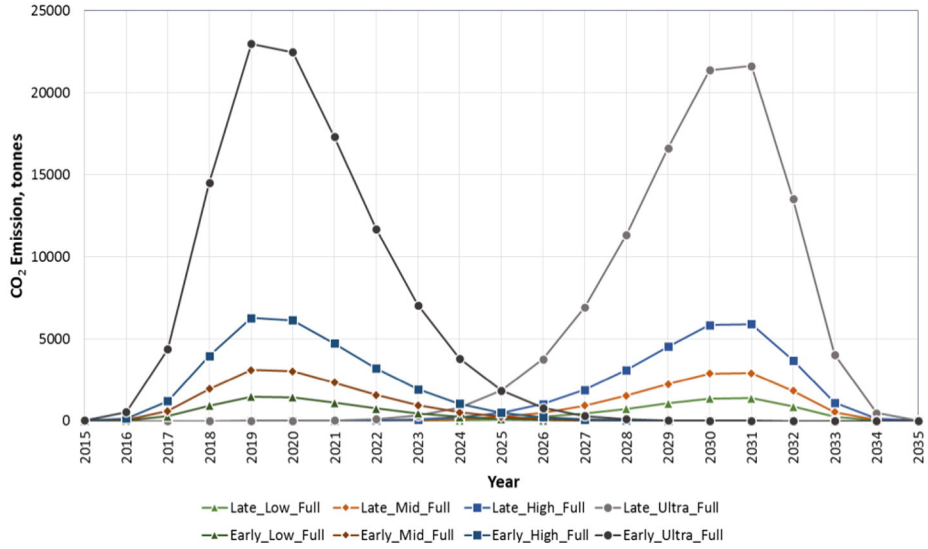

Fig. 6. Annual CO_2 emissions for 'early' and 'late' timelines, under 'low', 'medium', 'high' and 'ultra' scenarios, assuming full fracking water demand met by tanker and no re-fracturing.

to traffic emissions, and does not include use of diesel fuels for drilling or pumping, nor does it include non-CO_2 GHG emissions (i.e. methane) from well sites.

4. Discussion

We believe that the TIM model presented in this paper is a simple, yet flexible, approach to deal with spatial and temporal scenarios of fracking operations. It has been designed to be adaptable to different circumstances within any country, given available information on fleet characteristics, road type data, road quality data and haulage length characteristics, though the default emission rate values are based on European assumptions, which can be substituted with another set of emission factors with little effort. Pad operations may be modelled as subject to a timetable of events, with the compound effects on the road network allowed to arise. The phase and period approach also may be adapted to different levels of maturity in the industry, from initial exploratory wells in rural locations, to fully-developed facilities using pipelines for the majority of water transfer.

However, the literature cited in the introduction to the paper, and the subsequent results from our exploratory scenario testing, raise a number of interesting points to be considered. We believe a case can be made for caution in discussing impacts, with clear separation in that discussion between local and broader impacts. Citing total fracking-related emissions, for an individual well, multi-well pad, or even a region may appear negligible compared to those associated with transport in the region as a whole, or those emissions associated with another, established industrial sector. However, this does not negate discussion and analysis of impacts at the local level, where short-duration but large-magnitude events may occur, to the detriment of local ambient air quality and noise.

Comparison of impacts or normalisation of additional emissions over a long temporal baseline can distort the reporting of possible impact, leading to underestimation and undervaluing of potential public exposure and response to those impacts. In this work, we have chosen to report impacts for a six-well pad over the period from initial pad development to completion of all wells. This leads to mostly single-digit percentage increases in emissions, for all road types considered.

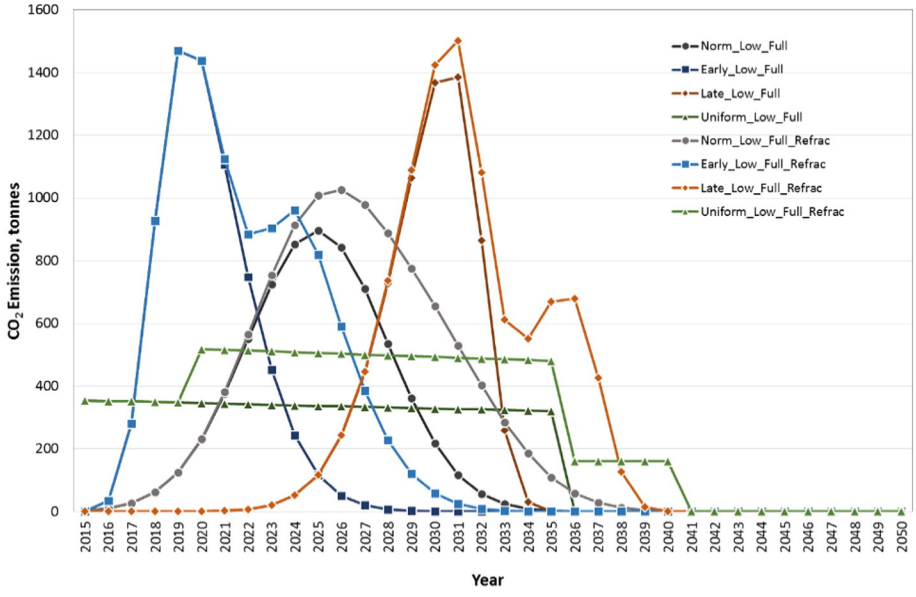

Fig. 7. Annual CO_2 emissions for all timelines, under low well development, assuming full fracking water demand met by tanker, with and without re-fracturing.

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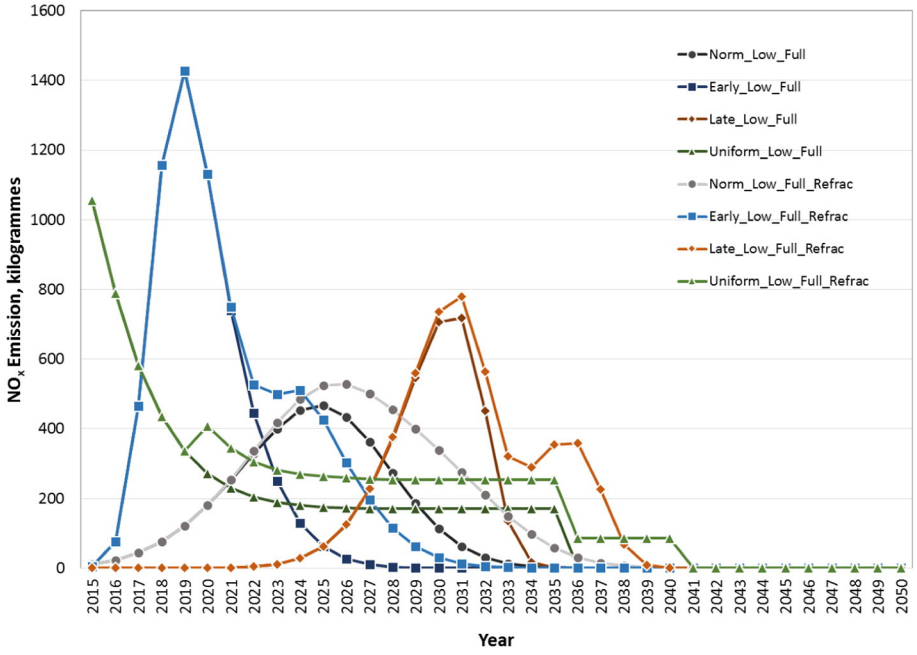

Fig. 8. Annual NO_x emissions for all timelines, under low development, assuming full water demand met by tanker, with and without re-fracturing.

Reporting over a longer baseline, e.g. the entire operational lifetime of a pad to decommissioning would result in negligible relative increases compared to baseline traffic impacts. However, examination of maximal results for phases with high traffic demand, even though the duration of those phases may be short, show substantial increases over the baseline, potentially leading to pollution exceedance events and breaches of local air quality standards, or increased annoyance and sleep disturbance in relation to noise.

A key, fundamental issue in the current discussion of fracking operations, identified through model development, is the considerable uncertainty in a large number of associated parameters, including, but not limited to, the overall scale of operations within a region, the individual water and waste demands at specific pad locations, and the amount of supporting infrastructure (both in terms of the underlying road transport network, and in the water supply network that could mitigate need for road transport) are all critical. For example, fracking activities in the UK may be more able to follow existing onshore oil and gas exploration practice with water supply by pipeline, thus reducing reliance on road tanker transport. Much of the literature examined giving the possible scope, demands and impacts of fracking in Europe cite experience from the US especially that contained in New York City and state documents (NYC DEP, 2009; NYS DEC, 2011). Ultimately the number of wells may well be determined by public acceptability, as well as economics and geology.

Whilst the impact of an individual pad or well may relatively be low and generally localised, multiple pads operating in a region can have a non-linear compounding effect on those localised impacts, "particularly in a densely populated nation" (Broderick et al., 2011) such as the UK or other EU member states. The traffic assignment sub-model in TIM, using the 'speed-flow curve' approach is recognised as simplistic, with a potential lack of compounding congestion effects potentially leading to an under-prediction in modelled emissions. A subsequent enhancement will be the linking of the traffic demand sub-model to a microscopic traffic modelling framework for comparison to PITHEM calculated results, as per the methodology of O'Brien et al. (2014).

Current results from the TIM are based on hypothetical assumptions. Additional data is being sought to further enhance capability, with the intention of performing Monte-Carlo analysis to give additional data

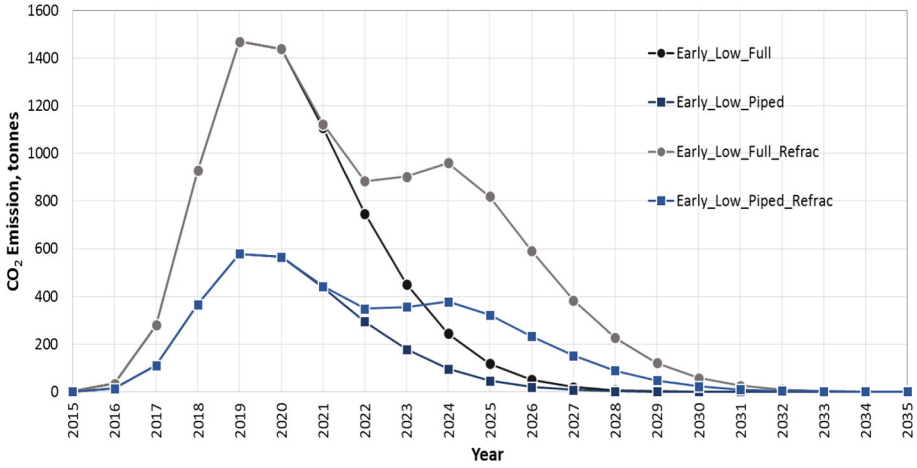

Fig. 9. Annual CO_2 emissions for the early uptake timeline, under low development, assuming either full demand for fracking water met by tanker or 90% met by pipeline, with and without re-fracturing.

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Table 3
Comparison of transport impacts model to Broderick et al. (2011).

Source	Broderick et al. (2011)	TIM	TIM	TIM	Broderick et al. (2011)	TIM	TIM	TIM	
Year	2010	2010	2015	2020	2010	2010	2015	2020	
Scenario	Low	Low	Low	Low	High	High	High	High	Unit
uCO_2	38.0	35.1–38.8	34.9–38.3	34.6–38.2	58.7	53.4–58.9	52.6–58.1	52.5–58.0	t/well
NO_x	–	171–253	54.4–111.2	11.9–21.3	–	261–385	83.3–170	18.3–44.0	kg/well
pNO_2	–	22.7–32.6	6.3–12.2	1.2–2.9	–	34.7–49.6	9.6–18.7	1.9–4.5	kg/well
PM_{10}	–	6.4–8.7	4.1–6.5	3.4–5.9	–	9.8–13.2	6.3–10.0	5.2–9.0	kg/well
$PM_{2.5}$	–	4.9–5.9	2.8–3.9	2.1–3.3	–	7.5–9.0	4.1–5.9	3.2–4.9	kg/well
HC	–	5.6–6.6	1.0–1.2	0.3–0.4	–	8.5–10.1	1.6–1.9	0.4–0.5	kg/well
L_{Aeq}	–	0–0.15	0–0.15	0–0.15	–	0.01–0.20	0.01–0.20	0.01–0.20	dBA
ESAL	–	4.9	4.9	4.9	–	7.4	7.4	7.4	×1000 axles/well

on the distribution and range of results. Our results do demonstrate that, even for a single, multi-well pad, relative impacts are disproportionate to VKT increases, especially for the case of axle loadings.

The expected technology improvements arising from the Euro class regulations are critical to the emissions calculations. Traffic-related NO_x emission rates per well in the mid-2020s are presently modelled as only 7%–11% of those of an operation commencing a decade earlier, based on the EFTv5.1.3 factors. However, there are potentially systematic issues with NO_x/NO_2 modelling predictions from road transport. Reductions in tailpipe emissions expected through the introduction of the EURO V and VI standards, forming part of the emissions assumptions in the EFT, have not been reflected in measured concentrations. The reasons for these discrepancies are discussed at length elsewhere (e.g. Carslaw et al., 2013) and remain an area of active research for both LDVs and HDVs. It is anticipated and understood that NO_x emissions rates will need to be updated as more knowledge on the real-world performance of EURO V HDVs, but especially EURO VI vehicles come to light. Performance of EURO V HDVs using de-NO_x catalysts (SCR), in conjunction with particle traps, has not lived up to initial promise. Oxley et al. (2012) suggest that the current EURO V/VI situation is "effectively equating to a failure of the EURO standards" in urban areas, though initial EURO VI on-road trials were encouraging (Hagman and Amundsen, 2013), with EURO VI HDV NO_x emissions potentially being lower than those for LDV diesel vehicles. Another future avenue of work is the use of the TIM to examine emissions under alternate HDV fuel scenarios, such as Compressed Natural Gas (CNG), Biomethane or, ultimately, hydrogen (Oxley et al., 2012; Pang and Murrells, 2013). Modelling of particulate emissions and resuspension from unpaved roads is another area requiring attention.

An integrated approach of using PITHEM in conjunction with air-quality modelling tools has already been demonstrated (Goodman et al., 2014), and subsequent heath impact or environmental justice analysis (O'Brien et al., 2014) represents an area for future work. The CNOSSOS-EU approach for noise mapping exposure assessment is also an active subject, with the methodology being relatively untested for real-world scenarios. There is also the possibility of embedding the TIM within a larger life-cycle assessment (LCA) framework for a more holistic approach to analysis, exemplified by the US GREET (Argonne, 2014) or Canadian GHGenius (NRC, 2013) models.

The disproportionate increases in ESAL found in the non-motorway cases are a cause for concern. It is likely that such roads were not originally designed with substantial volumes of HDV traffic in mind, and, given current economic conditions, may not fall on relevant authorities priority lists for reconstruction. Further assessment of impacts is problematic, given the diverse range of road ages and construction types possible. In older bituminous roads the main structural element of the roads, the roadbase, may have cured sufficiently to be able to withstand HDV loading, though surface layers may have aged, become brittle and be subject to cracking. Conversely, newer roads that have not reached full structural strength could be induced to failure early in their lifetimes (Nunn, 2000).

5. Conclusions

This paper has introduced a Traffic Impact Model (TIM) for studying the environmental impact of hydraulic fracturing operations. Implementation of the model has involved development of a traffic demand model for fracking operations, an abstract traffic assignment model to represent road network effects, and linking both to pre-existing, environmental modelling software that implements a number of standard approaches to assess GHG, local air quality, noise and axle loading impacts on roads.

Exploratory analyses using the model have revealed that the traffic impact of a single well pad can create substantial increases in local air quality pollutants during key activity periods, primarily involving the delivery of water and materials for fracking to the site. Modelling of

Table 4
Summary of results from minor road network scenarios.

Scenario	No. of wells	Fracking water supply	Refrack	Fracking + flowback water, Mt	VKT, million km	CO_2, kT	NO_x, T	PM_{10}, T
Low	190	Tanker	No	3.53	8.20	6.6–6.9	3.8–5.9	0.84–0.87
		Tanker	Yes	5.30	12.30	9.7–10.2	5.1–7.7	1.26–1.29
		90% pipe	No	1.38	3.23	2.5–2.7	1.3–2.4	0.33–0.34
		90% pipe	Yes	2.08	4.86	3.9–4.1	2.0–3.1	0.49–0.51
Medium	400	Tanker	No	7.44	17.26	13.9–14.5	7.1–12.5	1.77–1.82
		Tanker	Yes	11.16	25.89	20.6–21.6	10.7–16.2	2.68–2.71
		90% pipe	No	2.92	6.82	5.4–5.7	2.8–5.0	0.70–0.71
		90% pipe	Yes	4.37	10.23	8.1–8.6	4.2–6.4	1.05–1.07
High	810	Tanker	No	15.07	34.95	28.0–29.4	14.5–25.3	3.59–3.68
		Tanker	Yes	22.59	52.42	41.7–43.8	21.7–32.8	5.39–5.50
		90% pipe	No	5.90	13.81	11.0–11.6	5.7–10.0	1.41–1.45
		90% pipe	Yes	8.85	20.71	16.4–17.2	8.6–13.0	2.13–2.16
Ultra	2970	Tanker	No	55.25	128.15	102.8–107.8	53.2–92.6	13.2–13.5
		Tanker	Yes	82.86	192.22	153.1–160.4	79.7–120.4	19.8–20.1
		90% pipe	No	21.65	50.63	40.5–42.5	21.0–36.8	5.20–5.33
		90% pipe	Yes	32.47	75.95	60.3–63.2	31.5–47.8	7.79–7.94

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NO_x emissions showed increases reaching 30% over non-fracking periods and noise levels doubling (+3.4 dBA), dependent on access policy implemented to the site, potentially exacerbating existing environmental issues. Normalisation of these values over a longer period, such as the time to completion of all wells on a pad, mitigates the 'raw values' but may present a distorted picture of the actual impact on the local populous.

Somewhat conversely, use of the model to explore hypothetical future technology timelines over a range of well development scenarios covering several decades, show that the overall impact to a region, or a country as a whole, appear somewhat negligible compared to general traffic or industrial activities, though it is recognised that the methodology used may underestimate emissions associated with network congestion.

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