Do opacimeters have a role in future diesel exhaust gas legislation?

By Mike Jones, Senior Controls Engineer at Hartridge Test Products, UK

Conventional opacimeters are rugged, reliable, low cost instruments, with a proven track record in type approval & in-service periodic testing. But they are at the end of the road faced with advances in emission control technology. Can they be updated to deal with EURO 4 & 5 technologies?

1) Regulations using opacimeters

EEC 72/306 specifies the opacimeter and test method in type approval testing.
Used for many years for steady state loaded testing, with a reference free acceleration performed, it has become less significant since particulate mass over a test cycle was introduced. Mass limits have been reduced over the years, while smoke limits remain the same.
More recently, Heavy Duty testing has introduced the ELR step load test with lower smoke limits (0.8 m^{-1} now, reducing to 0.5 m^{-1} in 2005). Environmentally Enhanced Vehicles (EEVs) using the ELR test have a pass limit of 0.15 m^{-1}.
This transient test is quite a searching one, usually showing a smoke peak significantly higher than steady state load levels.
In-service periodic testing is performed in many countries with opacimeters the sole emission test on diesel vehicles. Mostly default pass limits of 2.5 m^{-1} for naturally aspirated and 3.0 m^{-1} for turbo vehicles are applied.
It is worth highlighting the fact that there is some particle size measurement inherent in the smoke test, which does not exist in the mass test. Also that the most relevant legislative smoke tests are for transients which the accumulative mass tests cannot detail. Smoke measurement is therefore complementary to mass testing in legislation.

2) What is an opacimeter ?

Light is directed through a chamber of known length, typically 400mm long and an eye response optical sensor measures the intensity. Smoke is passed through the chamber and attenuates the light. See Fig.3. This allows the blackness of smoke to be calculated.
Blackness is expressed as the coefficient of light absorption, k, units m^{-1}.
Opacimeters typically have a resolution of 0.01 m^{-1}.
ISO 11614 defines opacimeter terms and principles.
Opacimeters are portable, reliable, rugged, low cost, and easy to use instruments with a fast response. Their output is a single value (as opposed to, say, a number/size distribution) making opacimeters ideal for pass/fail indication when used for periodic in-service testing.

3) Concerns about conventional opacimeters

Increasing concerns about the health effects of ultrafine particles together with the changing nature of diesel exhaust are making conventional opacimeters irrelevant tfor testing new vehicles. The areas of concern are:

Insensitivity to small particles.

Most secondary particles in diesel exhaust are in the 50 to 200 nm diameter range.
Particles of 200nm dia. or greater block green light according to their surface area.
Particles of 50 nm dia. block about 15% of their surface area.
This means that large numbers of smaller particles barely register on a conventional opacimeter. Higher injection pressures of modern diesel engines potentially reduce particle size, increasing concerns about this limitation of conventional opacimeters.

Insufficient resolution
Smoke levels at the EURO 4 limit are near the resolution of a conventional opacimeter. Resolution needs to be increased, together with corresponding improvements in stability and noise to detect deterioration of EURO 4 engines to the limit.
Cross sensitivity to nitrogen dioxide
The fitting of oxidation catalysts and traps to exhaust systems increases the percentage of NO2 in the NOx from less than 10% to over 40%. Opacimeters read between 0.00016 and 0.00024 m^{-1} / ppm NO2, depending on the sensor bandwidth. For a typical 300 ppm NO2 concentration for modern engines, 0.06 m^{-1} of the reading is caused by nitrogen dioxide. This is 40% of an EEV pass level, intended to be for soot emissions. For engines fitted with an effective trap nearly all the signal will be caused by nitrogen dioxide.

4) Developing an advanced opacimeter

Taking account of particle size
Hartridge Test Products are using their opacimeter expertise to focus on the above concerns. The philosophy is to start with the proven, reliable, standard product as a base for development. Fig. 5 shows a prototype advanced opacimeter, fitted with a multiwavelength sensor head, powered from a 12V battery about to collect data on a road test. Fig. 6 shows the conventional smoke trace from the road test. Not a lot of interest here except perhaps a little concern at the amplitude of the transients for a EURO 3 vehicle. Such signals are not untypical for 2 year old EURO 3 cars when road tested.
Fig. 7 expands detail 1 of Fig 6 and shows the other wavelength traces and particle size determined by applying Mie theory. Note that with this range of sensors it is difficult to resolve particle sizes much above 200 nm dia. The displayed values of 220 nm indicate 220 nm or greater diameter. The initial peak is the start up of the engine. Note that all traces sit on top of one another, indicating large particles, probably the blowing of soot out of the exhaust. As the accelerator pedal is pressed the traces separate, indicating smaller particles.
Detail 2 in Fig 8 shows a couple of gear changes accelerating up a hill. Note the second peak has deviated from the more typical spread pattern of the first peak indicating, perhaps, inconsistent engine management during the transients. A sampling rate of 20 Hz allows transients to be examined in detail.
While particle sizing is interesting it doesn't fit easily into the periodic in-service test requirement of a simple pass or fail. A 'political' weighting factor could be introduced to multipy the k value by a 'danger' factor, for example maybe 80 nm dia. particles could have a factor of 5 to take account of the much larger number of particles required to give the same blackness as from particles greater than 200nm dia. and their ability to penetrate further into the lung.
Much simpler and less controversial would be to use the ultraviolet wavelength rather than the green as this at least makes more 'visible' what is there. Note that oil burning in gasoline engines is also strongly shown up by the separation of traces.

Increasing sensitivity
What level of k values for smoke can be expected from EURO 4 & 5 vehicles?
It is clear that opacimeters will never be sensitive enough to measure the soot output from a vehicle with an effective particulate trap. It is likely, however, that many vehicles will achieve EURO 4 without trap technology. The more relevant question is 'what k values can be expected from EURO 4 & 5 vehicles when emitting particles around the limit?' This is the value, with an appropriate deterioration factor, that a periodic in-service opacimeter would be required to detect.
Mass reduction called for is by a factor of 5 from EURO 3 to EURO 4 & 5, so a 10 times increase in sensitivity should be adequate. How does this agree with measurements?

EMPA June 2002 tests under the PMP program set out to simulate 40% cleaner than the EURO 4 pass limit. Fig 9 shows a trace from the ETC cycle with the mass level set for about 40% less than the EURO 4 limit. K values for transients were typically between 0.1 and 0.15 m^{-1}. Steady state loaded tests showed levels between 0.005 and 0.02 m^{-1}.
Fig 10 expands the detail of the first peak and adds for comparison the corresponding trace when the ETC cycle is run with an effective trap. It graphically shows how effective the trap is at clamping the soot output during a transient.
It appears that an opacimeter with improved sensitivity can effectively measure transients around EURO 4 limits, but further tests are necessary to establish if the EMPA simulation levels are typical.

Removing nitrogen dioxide effects

The red wavelength was illustrated for the EMPA test results because this is insensitive to NO2 and is therefore unambiguous as a measure of particulate at low levels. The other wavelengths show sensitivity to NO2 complicating analysis at these low soot levels. Red has the disadvantage of being less sensitive to small particles, so a simple switch to only this wavelength is not the answer. A range of sensors is necessary to separate the various effects.

5) The way forward

The challenge is to opacimeter manufacturers to address the concerns detailed above. Hartridge Test Products is working to this end. With the co-operation of legislators, opacimeter standards & periodic in-service test procedures need to be revised to keep up with changes in diesel emission technologies. It is highly unlikely that On Board Diagnostics will be mature or proven enough in the next 5 years to guarantee detection of all emission faults. An advanced opacimeter will be required to check compliance.

Mike Jones August 2002


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Fig.1
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Fig.2

OPACIMETERS IN LEGISLATION

EEC72/306	Loaded test at 3 speeds with a free acceleration recorded.		
	Establishes the smoke level of the vehicle.		
	Must be less than 2.5 m-1 (2500 mK) for N/A vehicle.		
	Test cycle mass test is more demanding (limits lowered)		
ELR	Stepped load load for HD vehicles		
	2000	limit 0.8 m-1	(800 mK)
	2005	limit 0,5 m-1	(500 mK)
	EEVs	limit 0.15 m-1	(150 mK)
In-Service	Periodic testing based on EEC 72/306		
	Used in many countries		
	Default values of 2.5/3.0 m-1 for N/A / Turbo		

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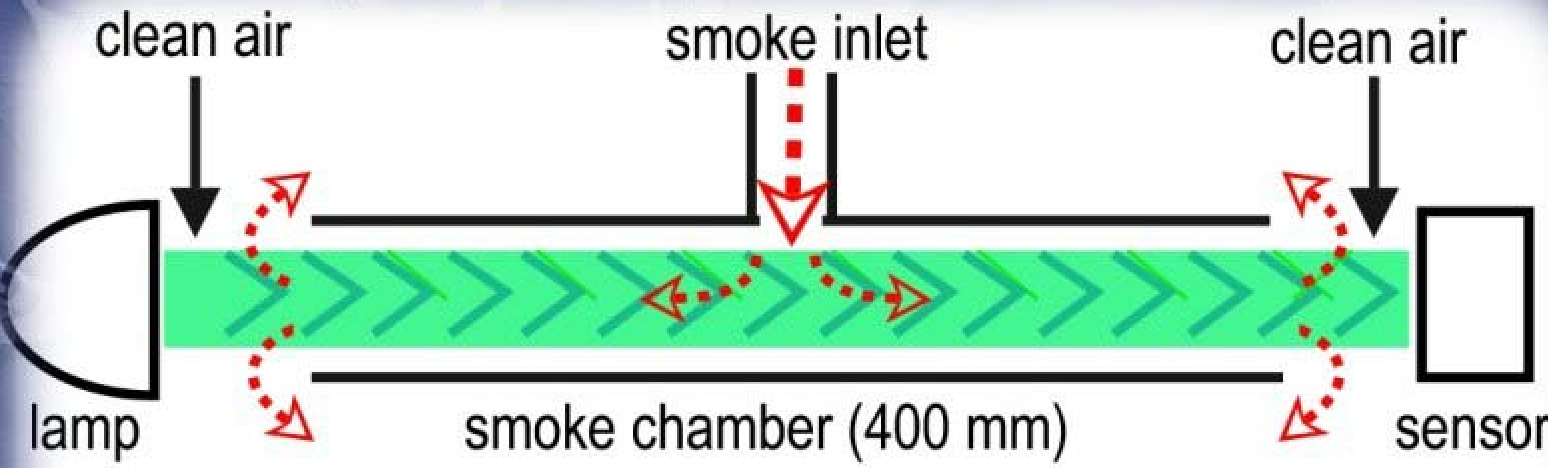
Fig3



OPACIMETER BASICS

* Measures 'blackness' of the smoke as seen by the eye
* Units are Coefficient of Light Absorption K (m-1)
* K represents particle blocking area (for larger particles)
* Typical resolution 0.01 m-1 (10 mK)
* Lowest pass limit in legislation is 0.15 m-1 (150 mK)
* Standards are defined in ISO 11614

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Fig 4

LIMITATIONS OF CURRENT OPACIMETERS

* Insensitive to small particles

200 nm dia. or greater block light according to their surface area
50 nm dia. block only about 15% of their surface area.

* Insufficient resolution for EURO 4 levels

0.001 m-1 (1 mK) needed together with improvements in noise and stability

* Cross sensitivity to nitrogen dioxide

Opacimeters read between 0.16 and 0.24 mK/ ppm NO_2.
At 300 ppm NO_2 (typical for modern engines) this is 40% of the reading at the EEV pass limit.

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Fig 5

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Fig 6

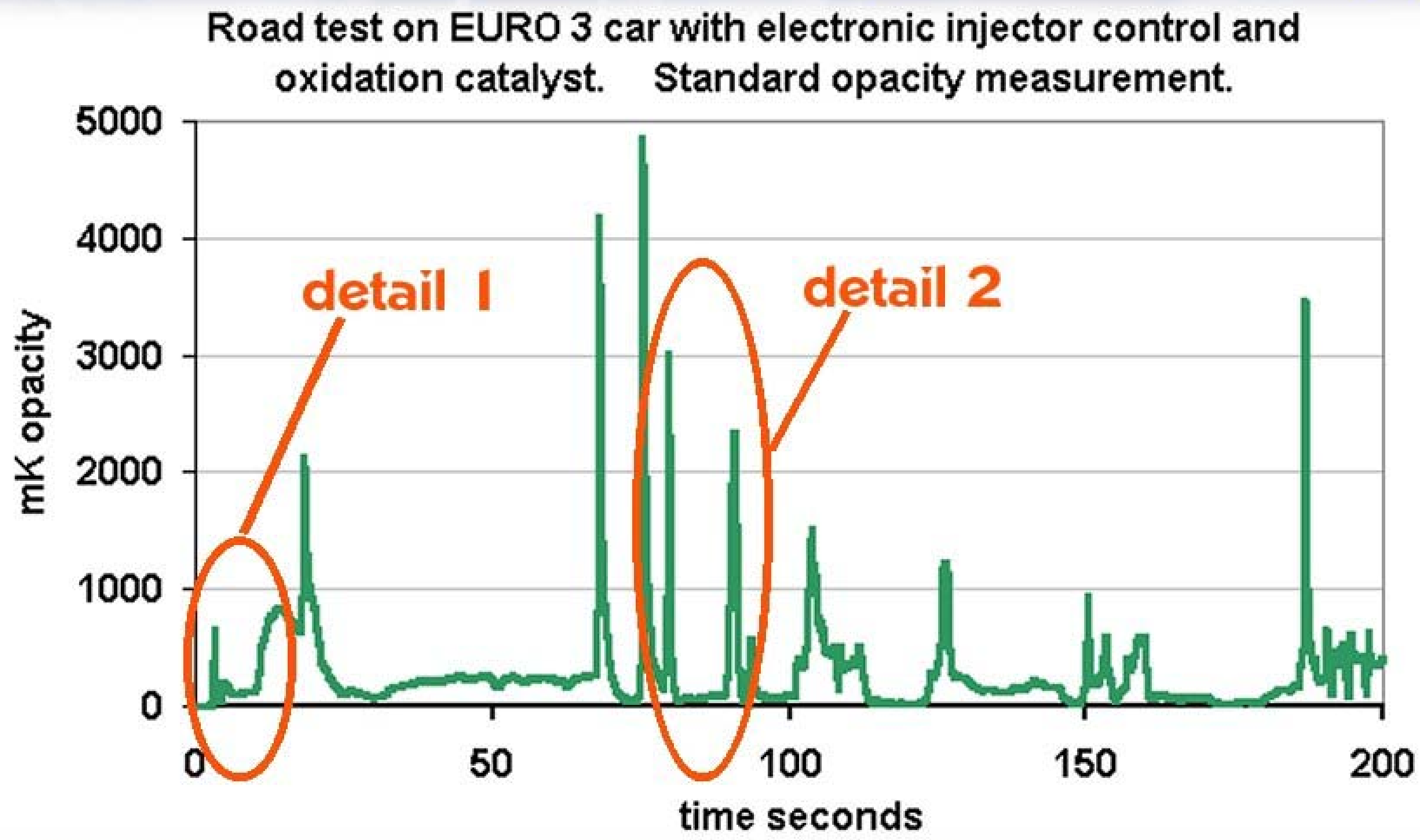

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Fig 7

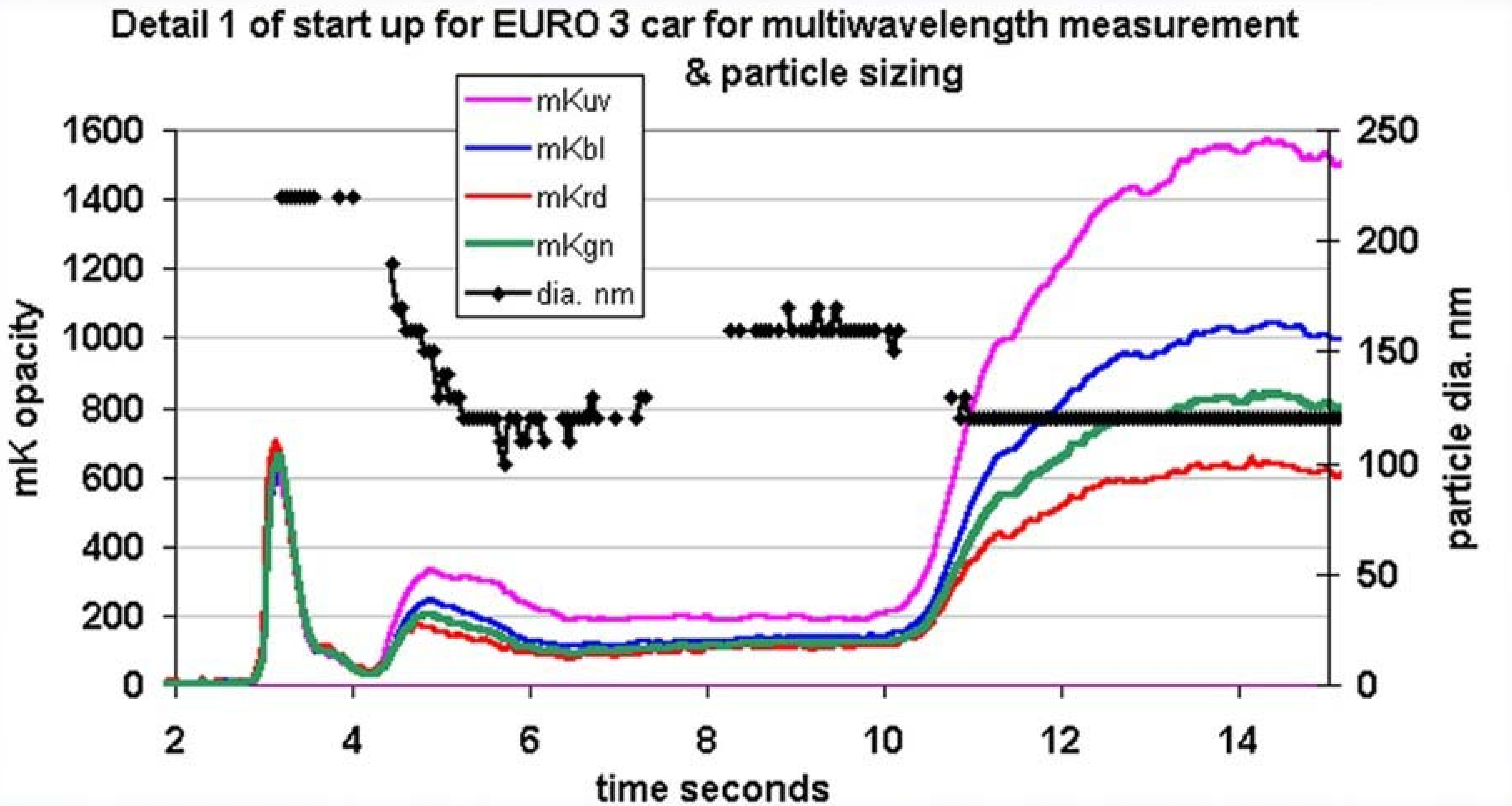

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Fig 8

Detail of road accelerations for EURO 3 car.
Multiwavelength measurement & particle sizing

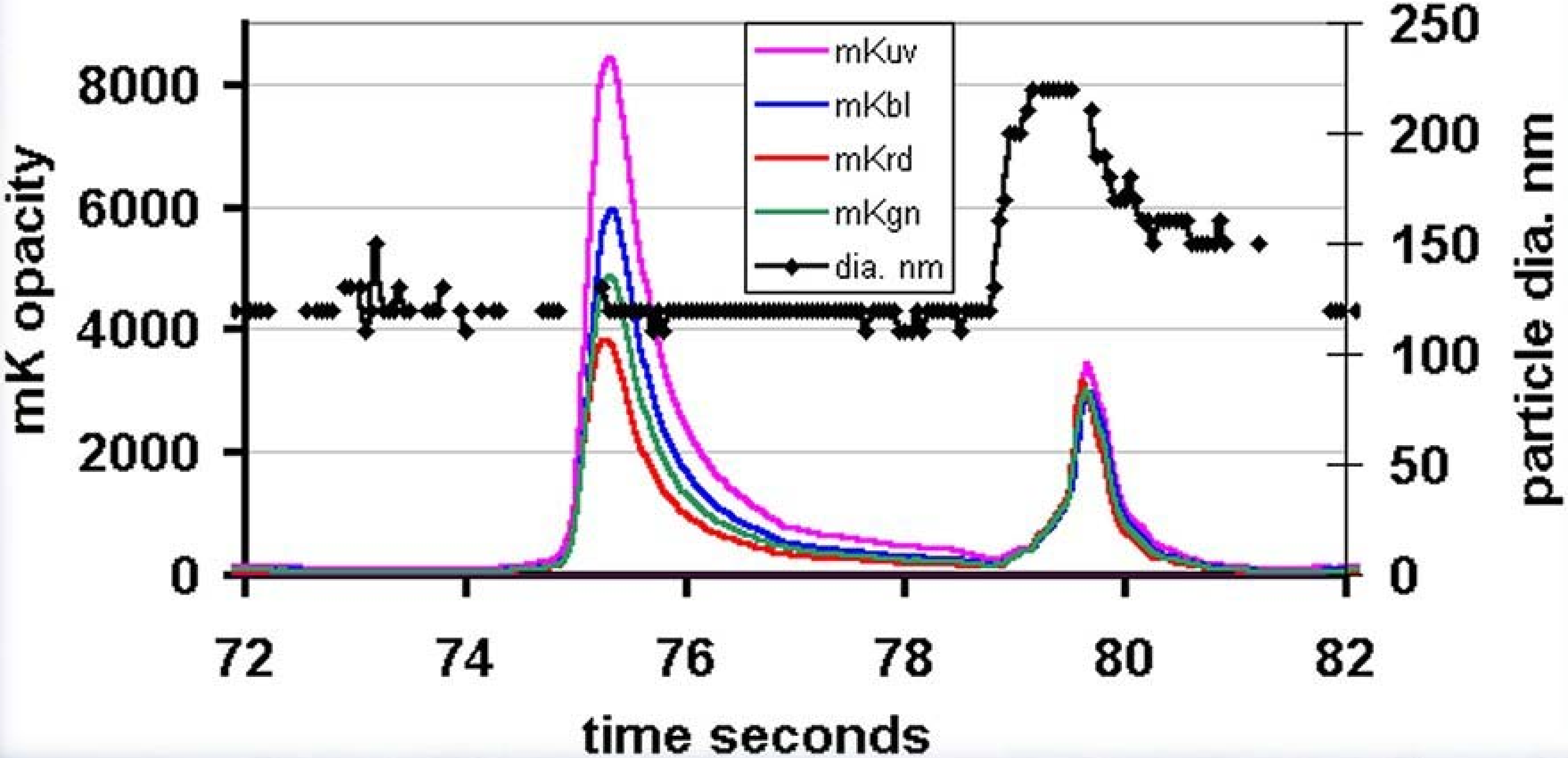

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Fig 9

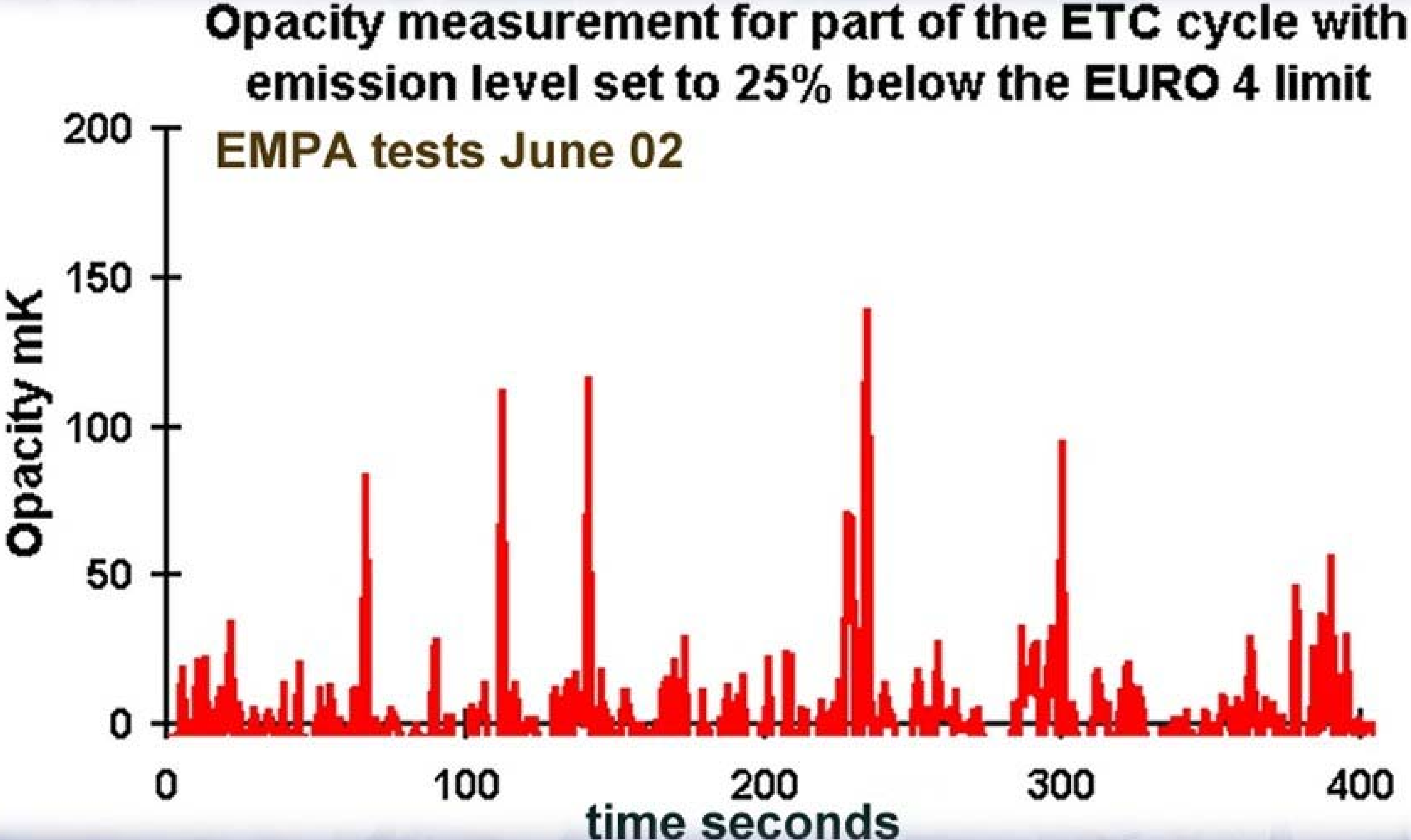

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Fig 10

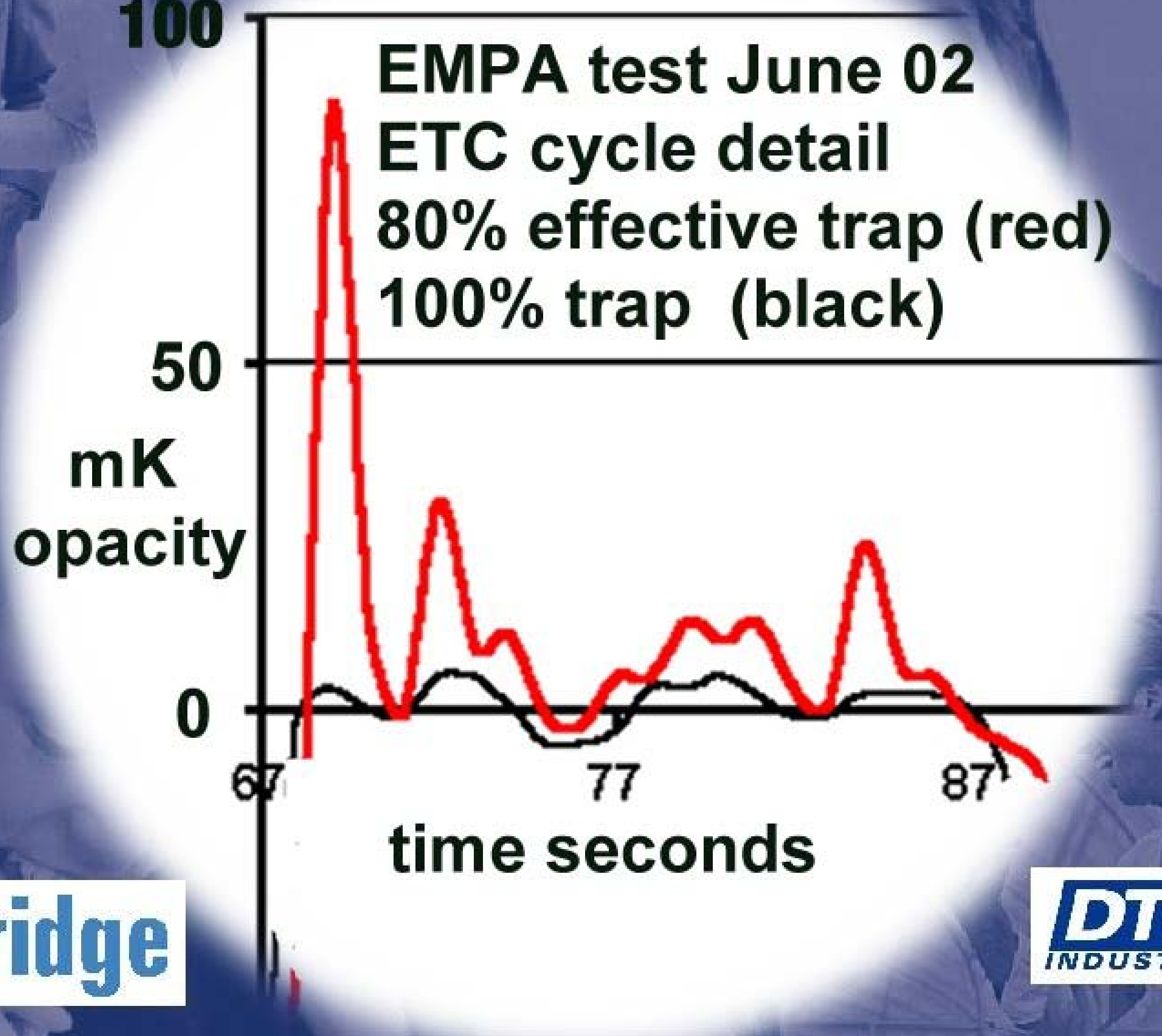

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Fig 11

THE WAY FORWARD FOR OPACIMETERS

- Update the spec. to take account of the limitations.
- Keep opacimeters in type approval for transient testing to provide reference levels.
- Apply new spec.meters for in-service testing allowing a degree of deterioration.
- When it is shown that OBD picks up all the emission faults, then opacimeters will finally be redundant.

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